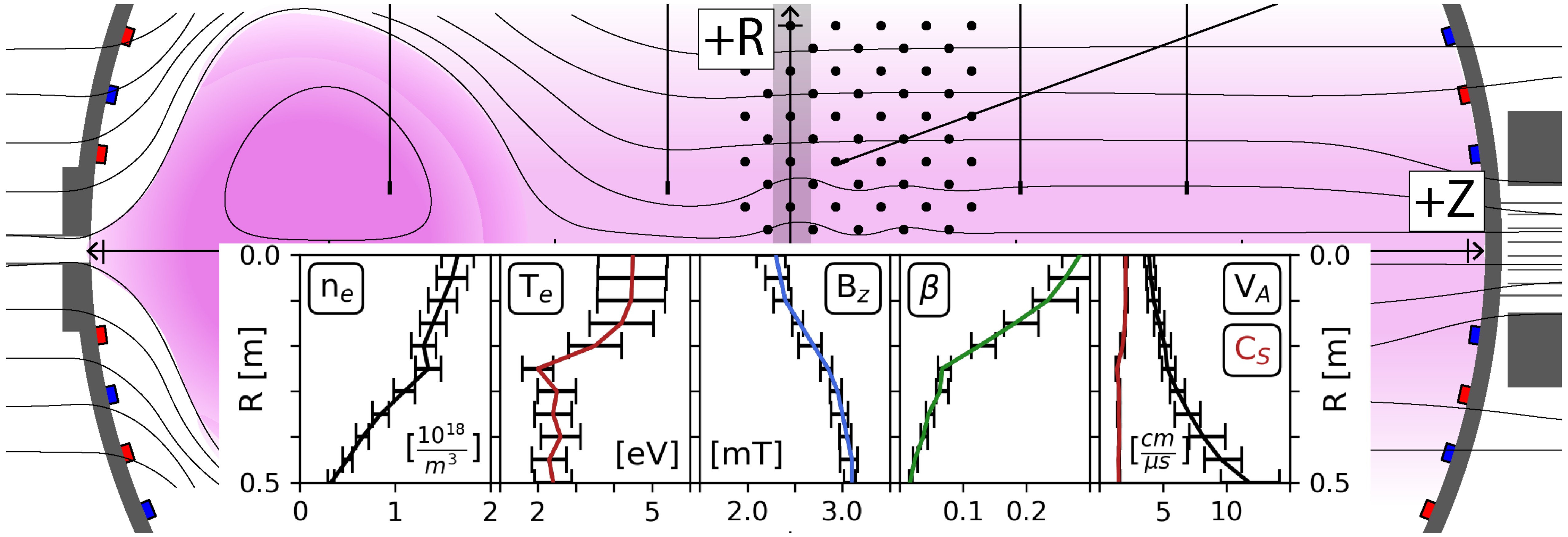
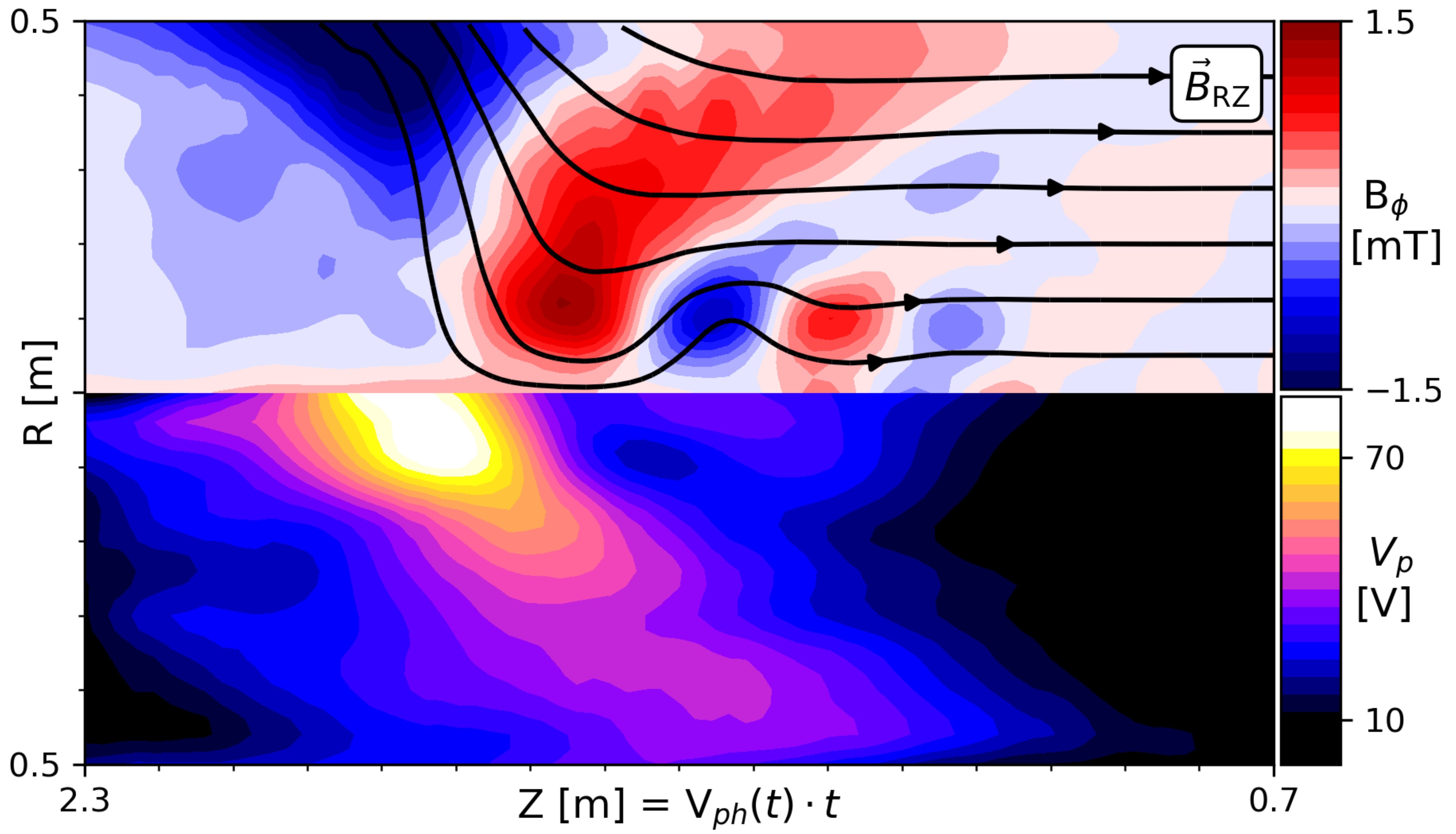
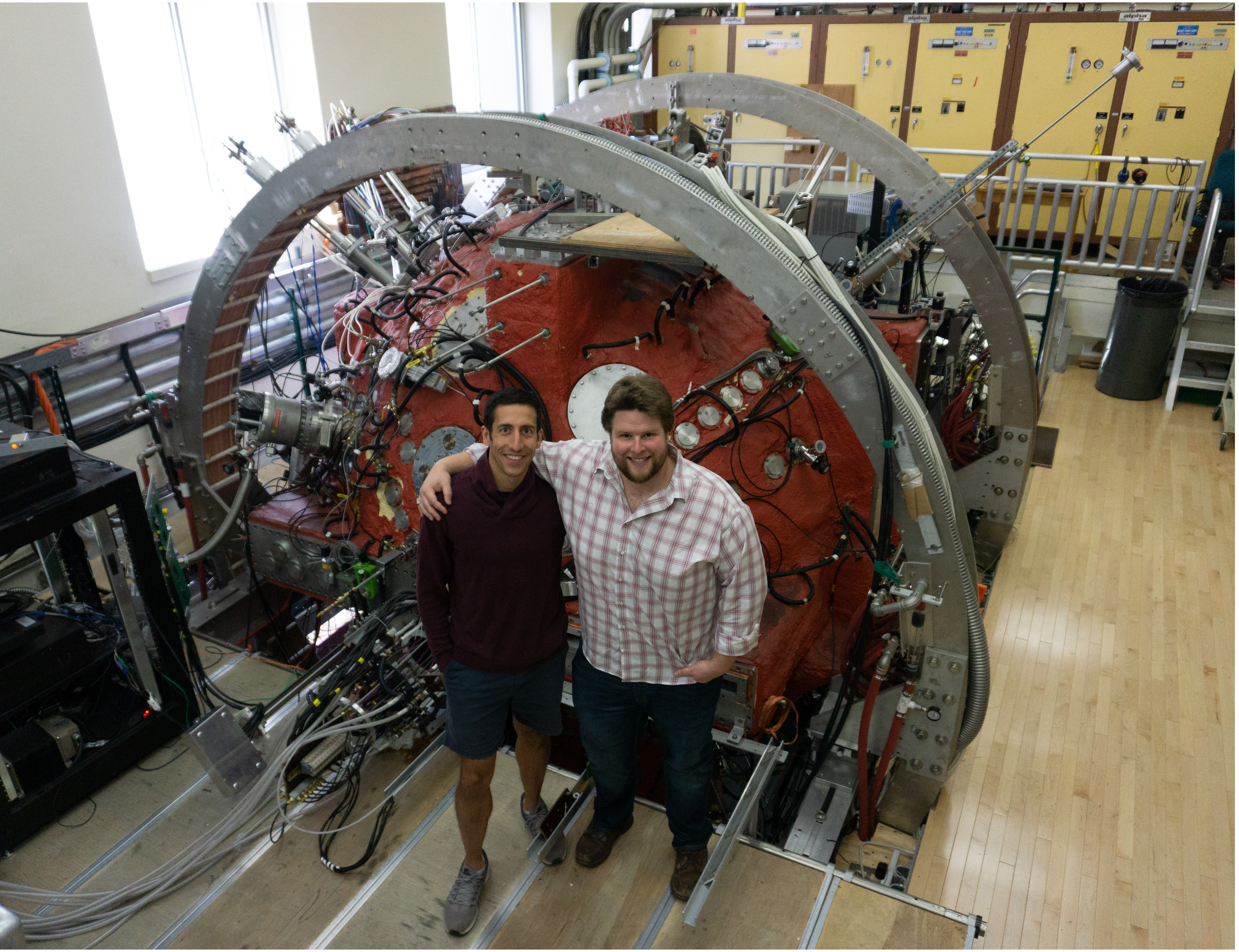
Parallel shock experiments on the Big Red Ball: Understanding the role of non-linear whistler waves





PPPL Heliophysics Seminar 2021-03-12
Doug (not yet Dr.) Endrizzi

The BRB is a platform for shock experiments



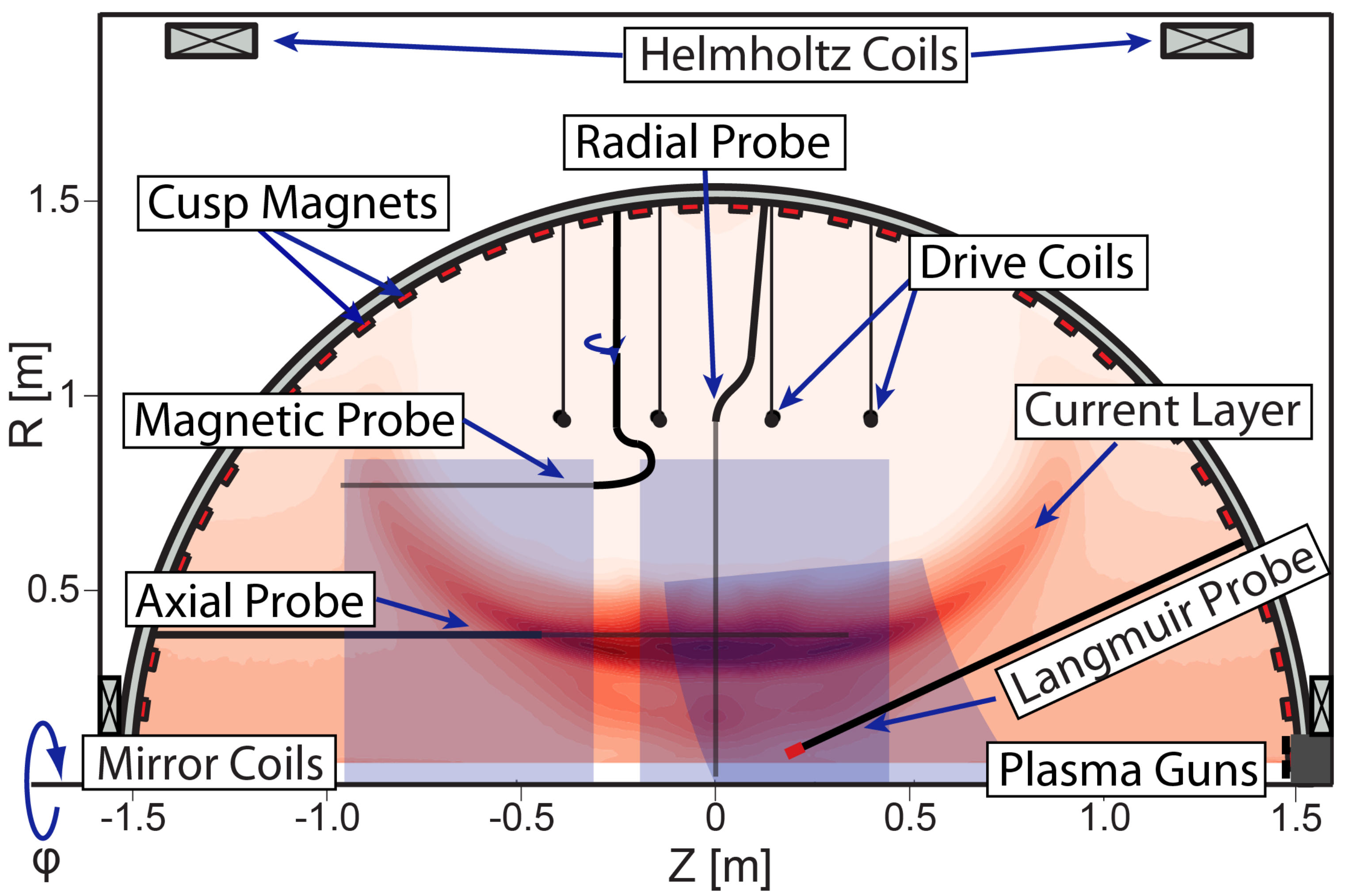
- Weak Magnetic Fields
  Small V_A
- Modest Te: 2 - 5 eV
  Small C_S
- Modest n_e: 10^{18} m^{-3}
  d_i ~ 20 cm
- ~100 km/s Piston
  Large M > 4
- Large Radius: 1.5 m
  Long Time Evolution

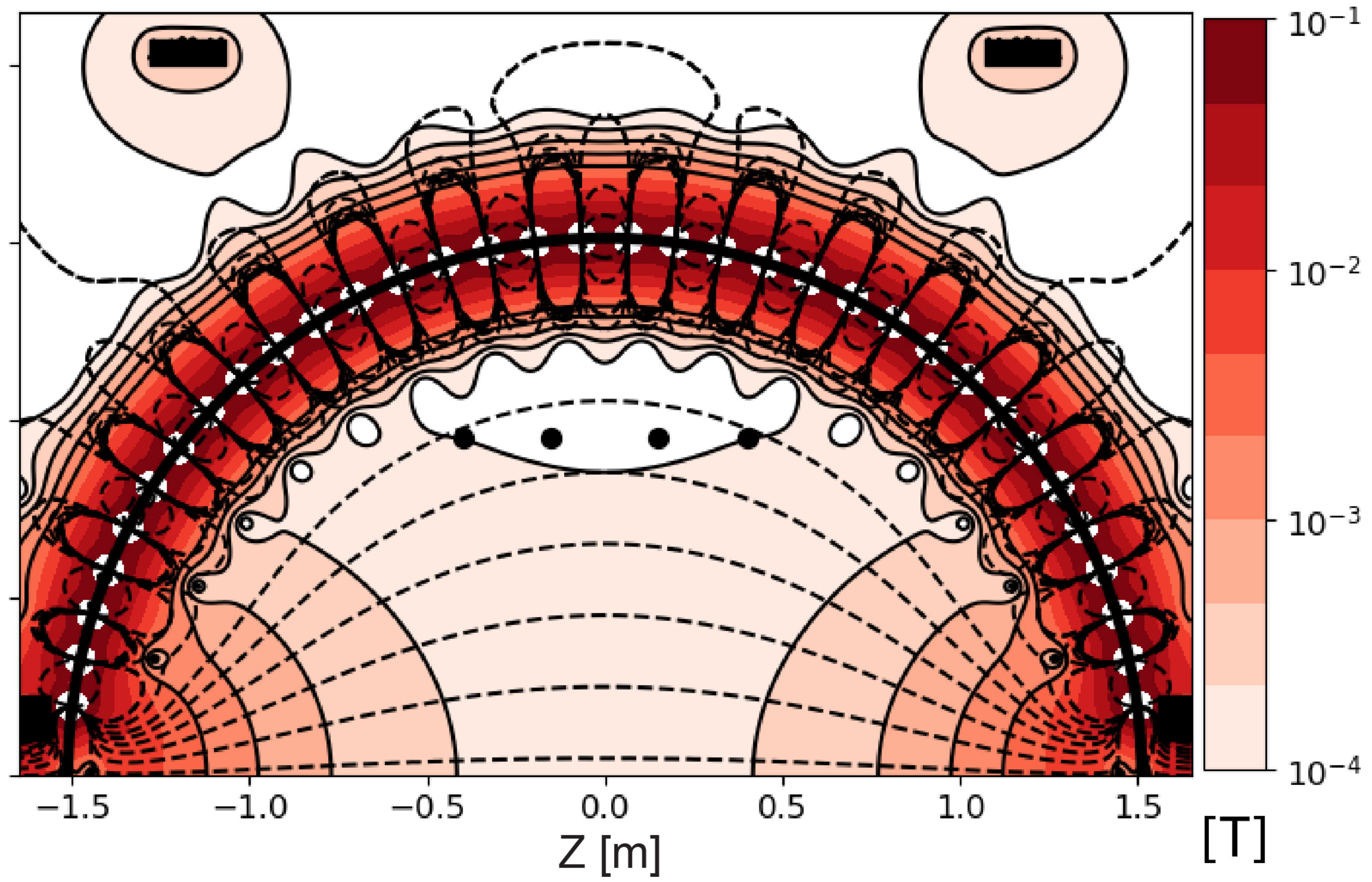
We explore both perpendicular and parallel cases

Perpendicular case:

$$\mathbf{u} \perp \hat{b}$$

- Theta Pinch
- Growing magnetic piston

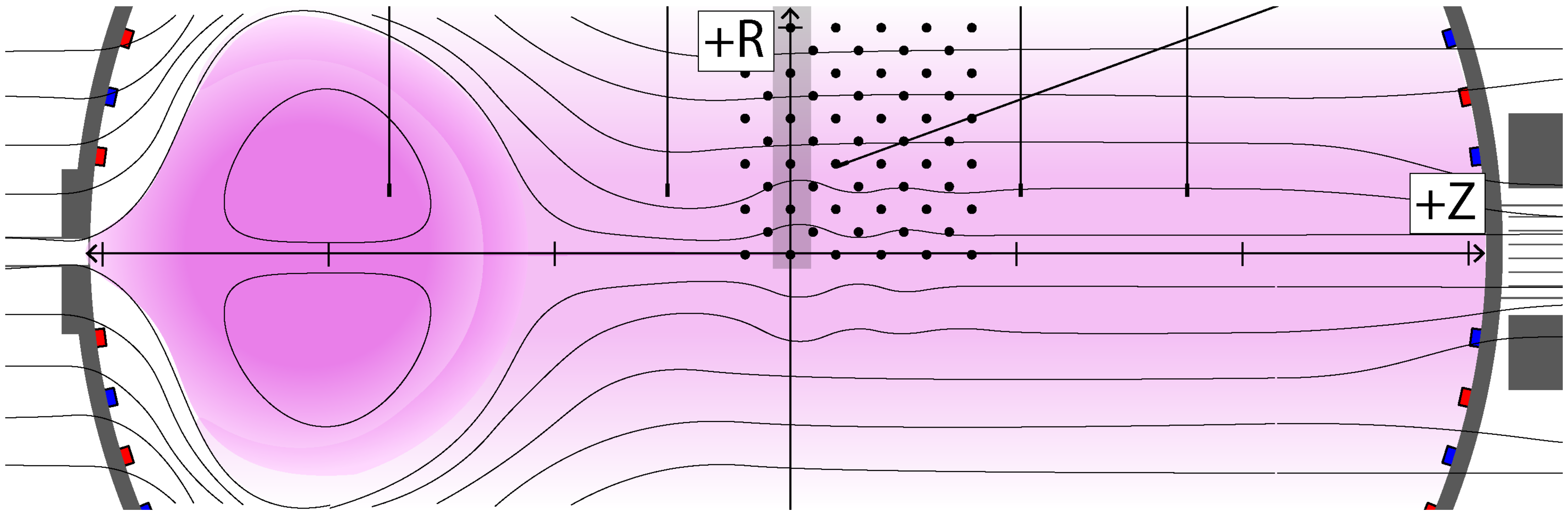




Parallel case:

$$\mathbf{u} \parallel \hat{b}$$

- Plasma Cannon
- Decaying kinetic piston



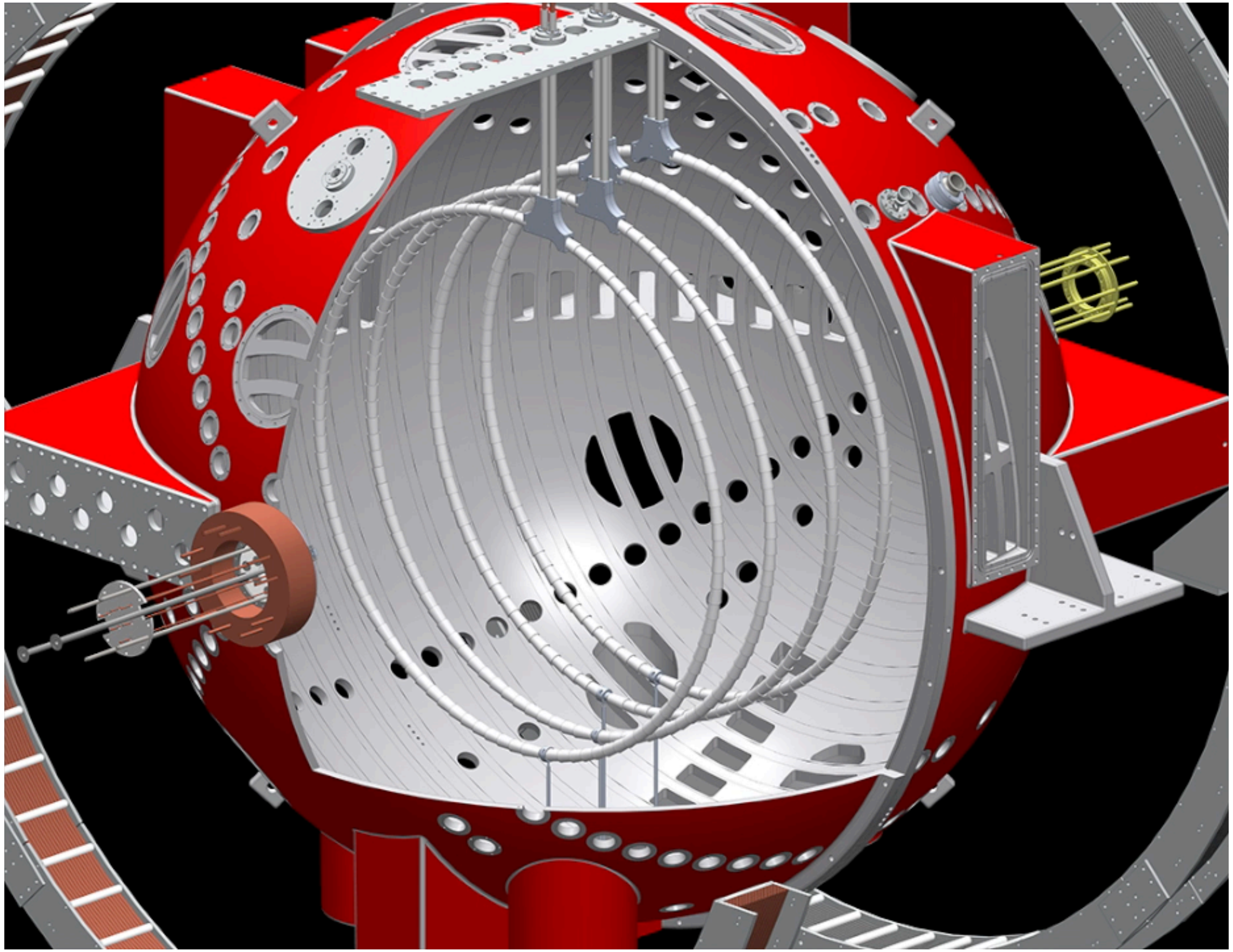
Theta pinch: Similar to earlier experiments, but larger

$n_e = 1 \cdot 10^{18}\ \mathrm{m}^{-3}$

$T_e = 2.5\ \mathrm{eV}$

$B_z = 0.5\ \mathrm{mT}$

$\beta_e = 4.0$

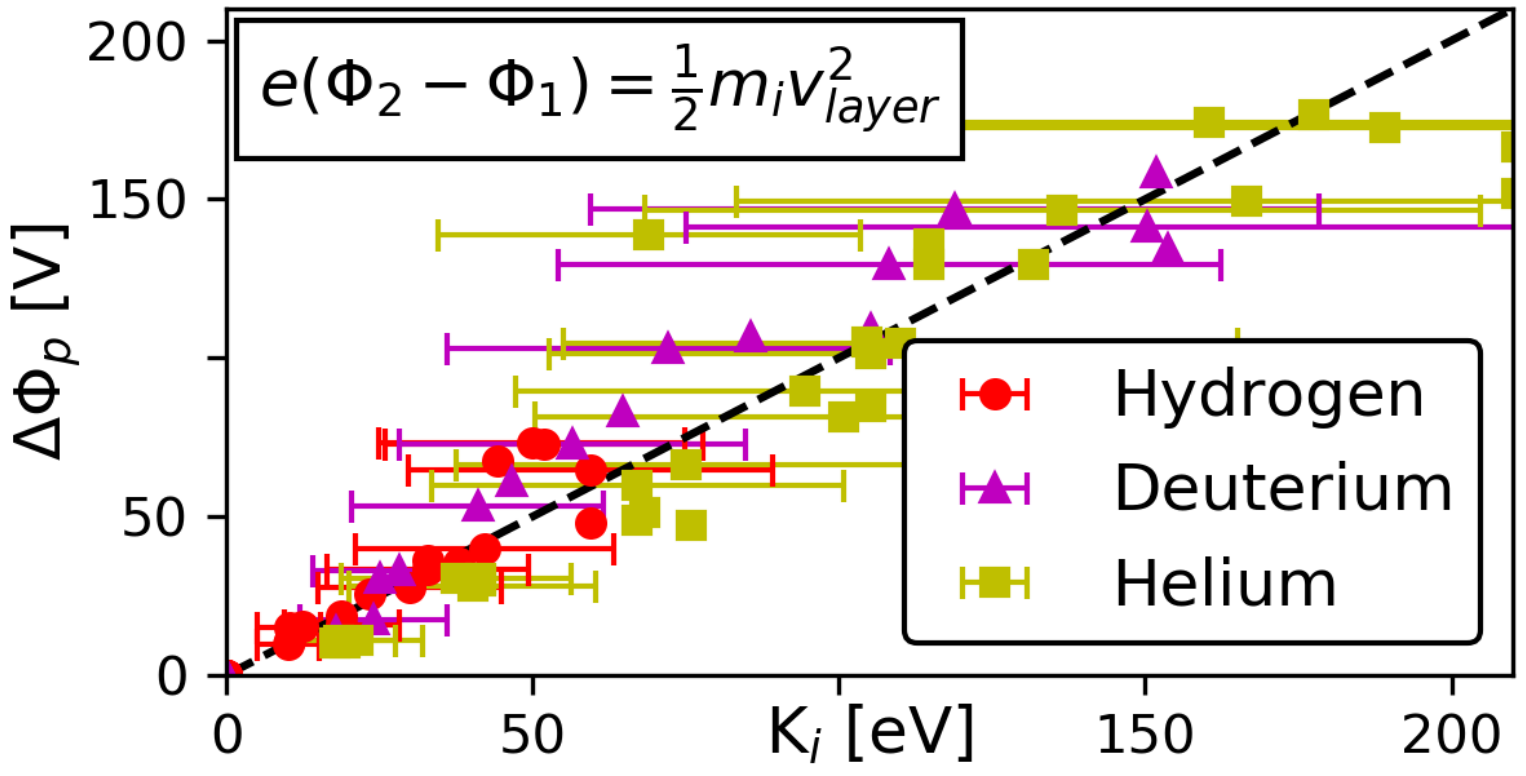


Accepted: Endrizzi, D. et al., (2021), Laboratory Resolved Structure of Supercritical Perpendicular Shocks, PRL

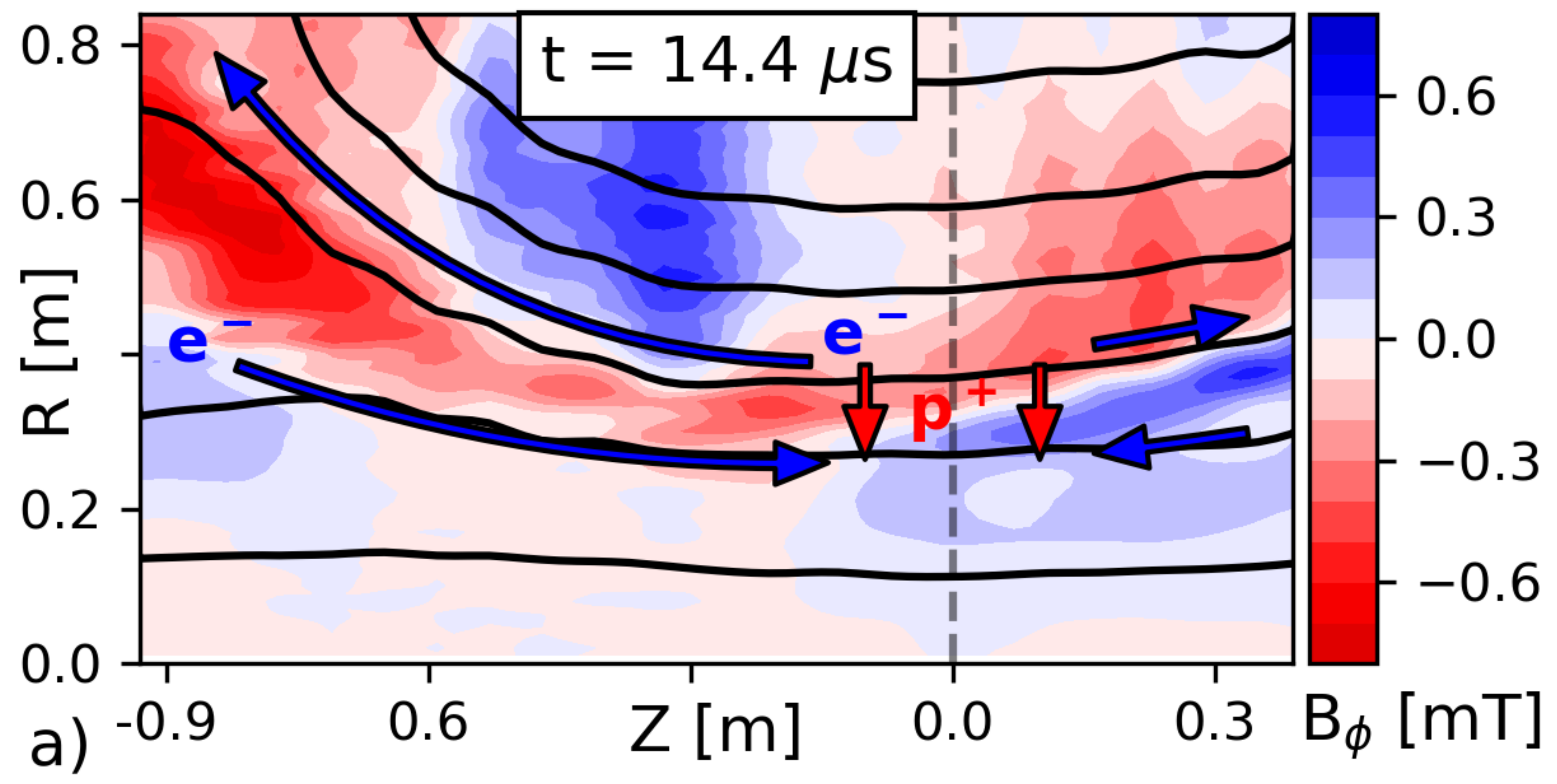
Two fluid effects are critically important

- Moving ambipolar potentials specularly reflect unmagnetized ions, and ram pressure sets penetration speed

$$(1+\alpha)\rho u^2 + nT + \frac{B^2}{2\mu_0} = n'T' + \frac{B'^2}{2\mu_0}$$

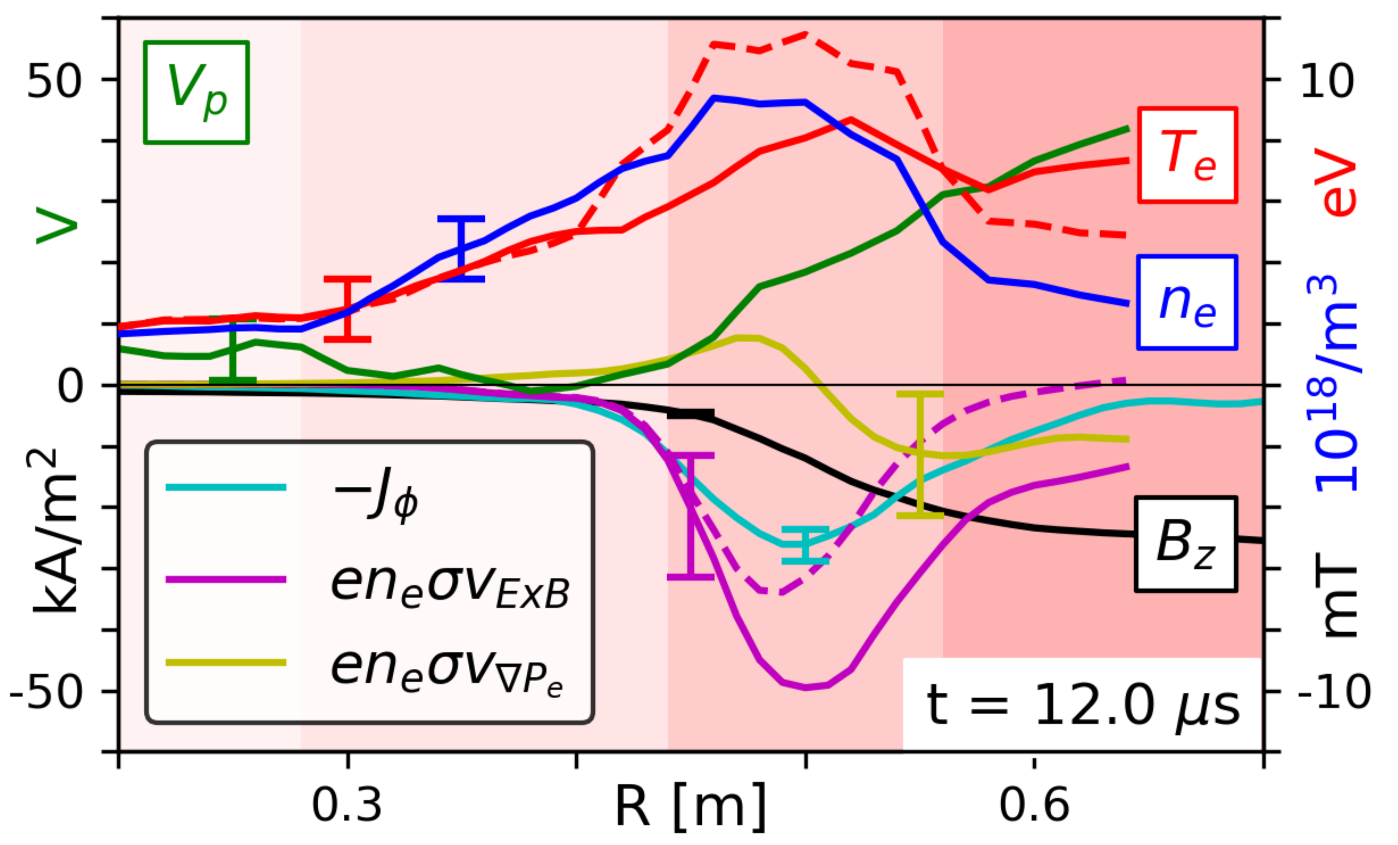


- Out of plane magnetic fields appear as a signature of Hall physics



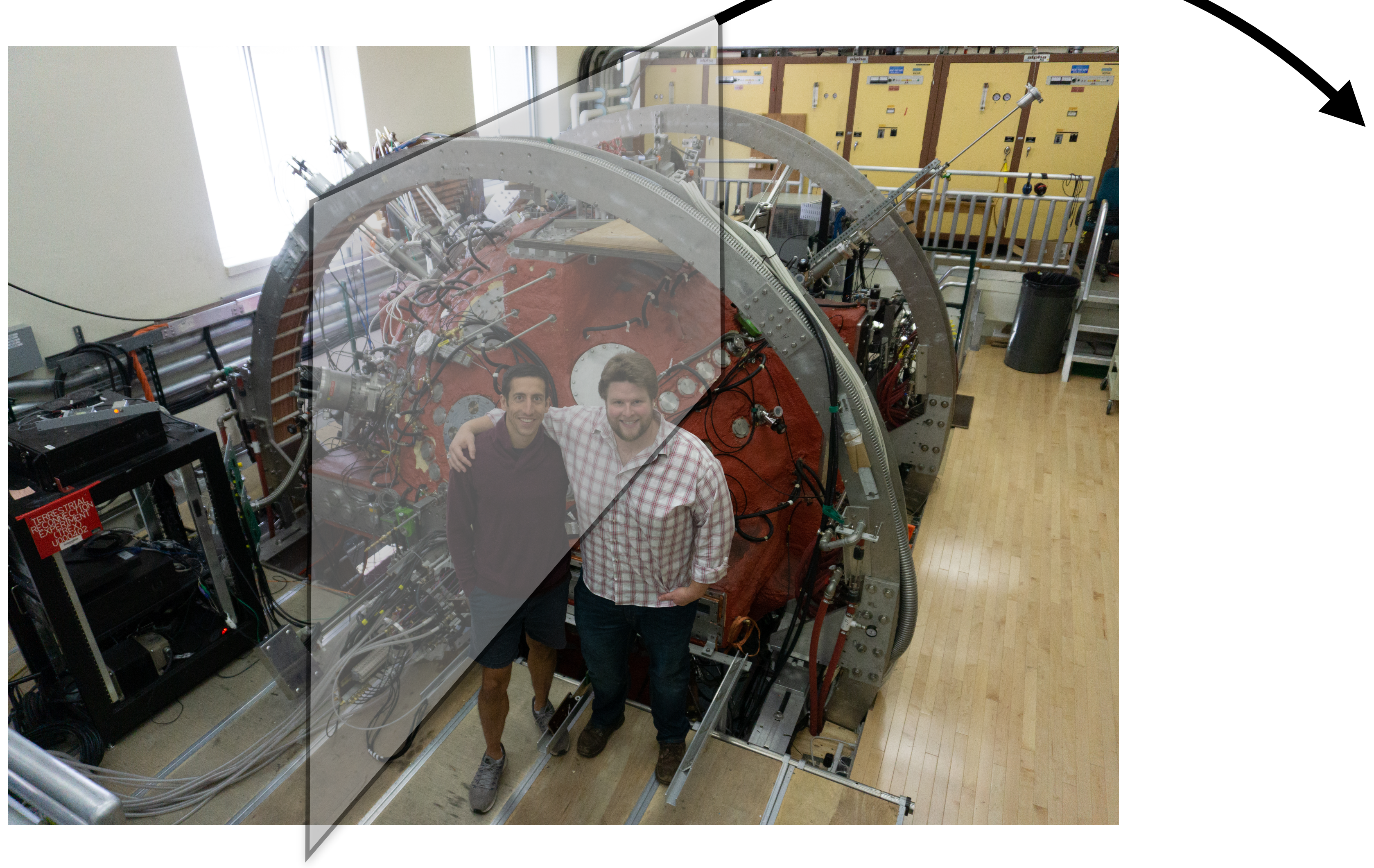
- Generalized Ohm's law accurately describes current layer behavior

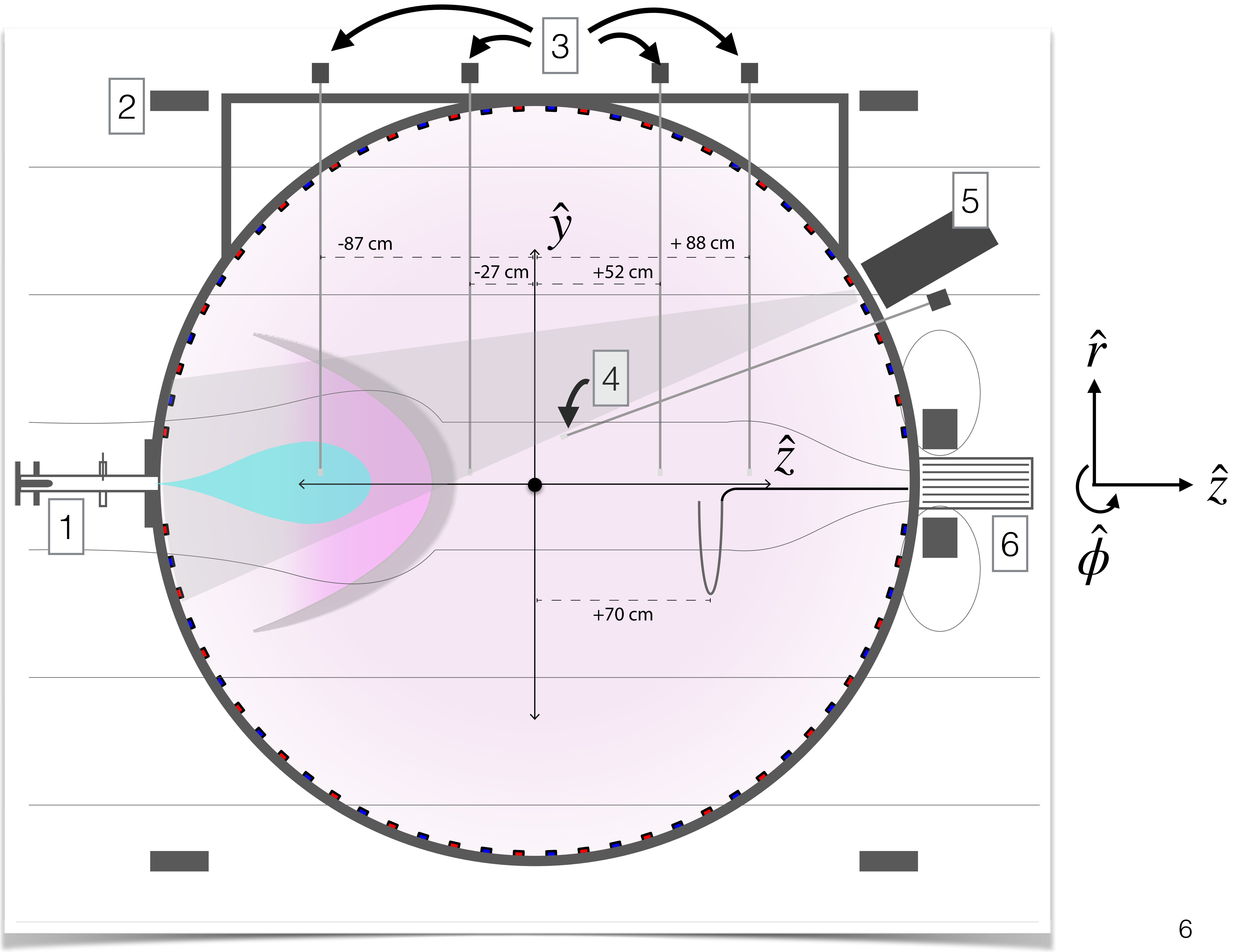
$$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{J} - \frac{\nabla P_e}{en_e} + \frac{\mathbf{J}\times\mathbf{B}}{en_e}$$



Accepted: Endrizzi, D. et al., (2021), Laboratory Resolved Structure of Supercritical Perpendicular Shocks, PRL

2020 Parallel Shock Experiment Configuration

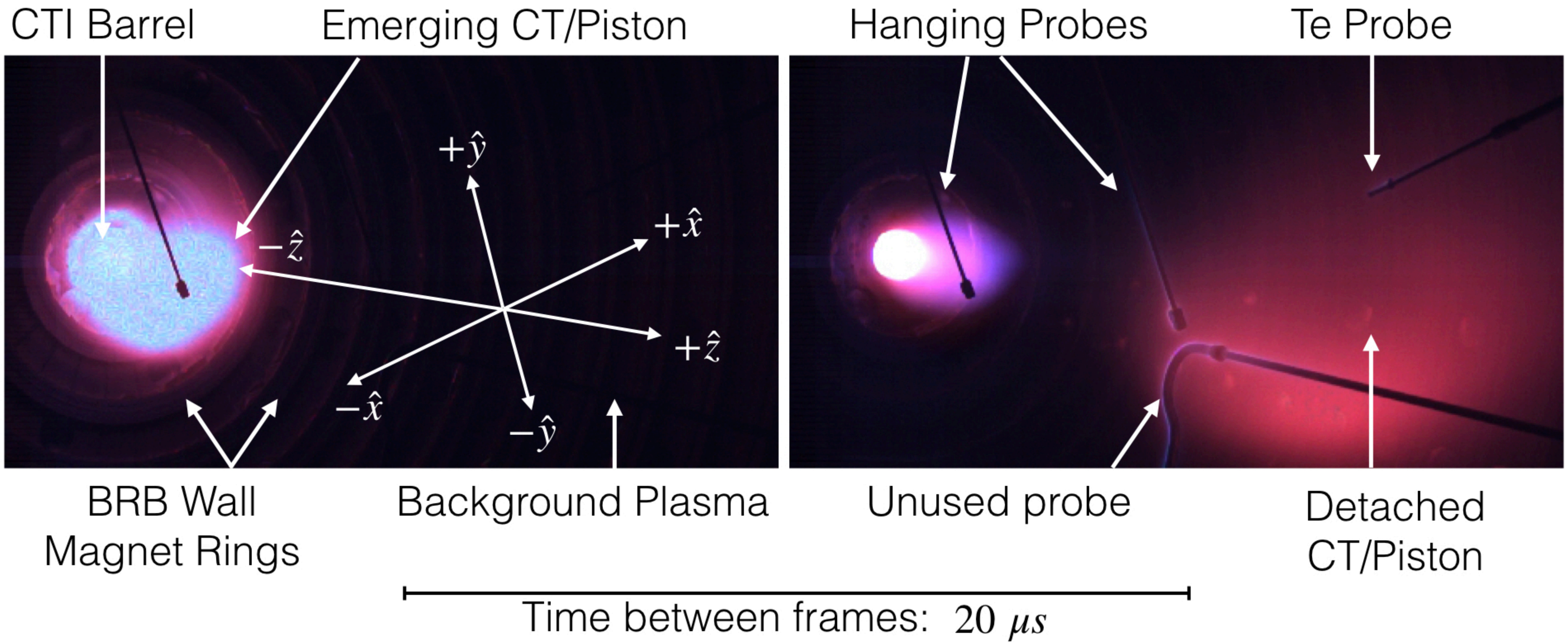




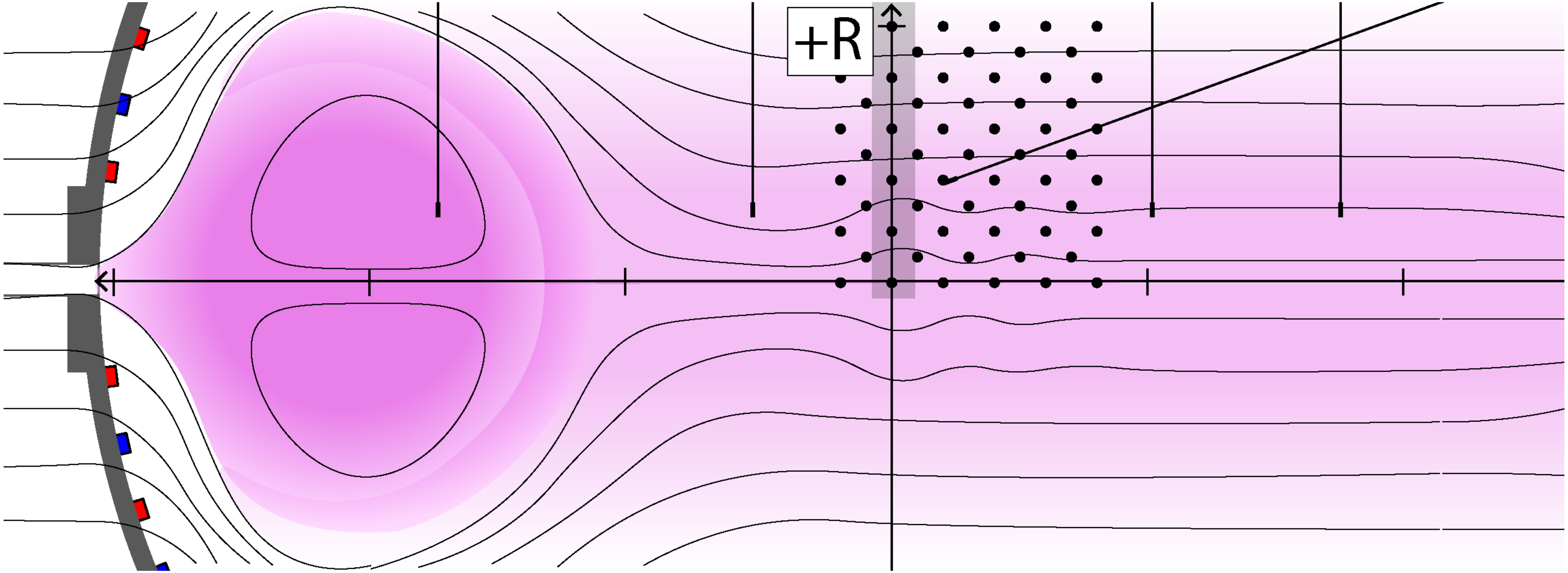
1. Plasma Cannon
2. Helmholtz Coils
3. Hanging Probes
4. Langmuir Probe
5. Fast Camera
6. Plasma sources

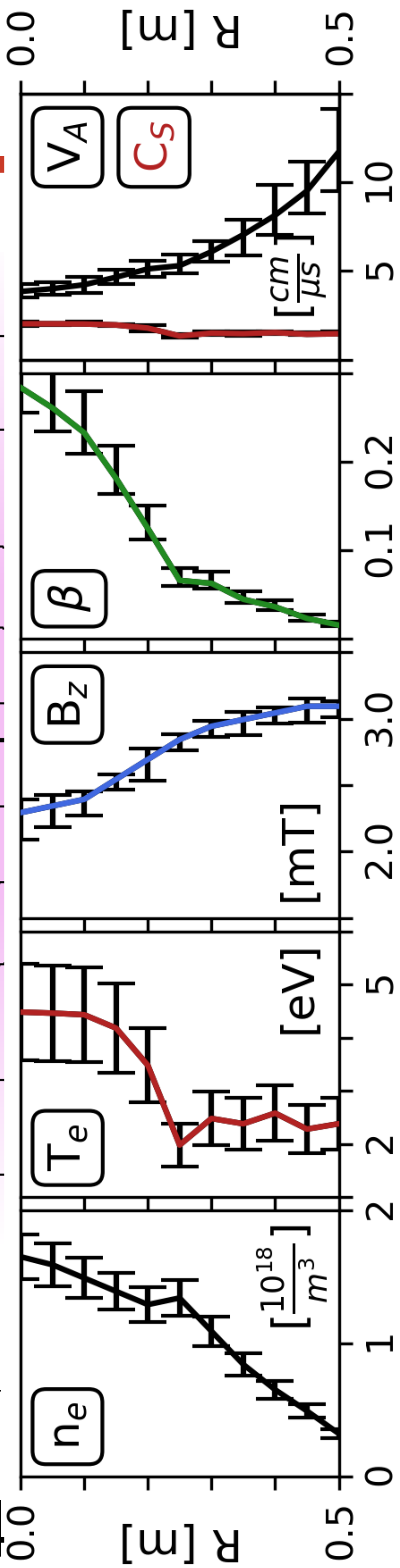
2020 Parallel Shock Experiment Configuration

Shot 48129, 3 Guns, B_0 = 9.0 mT



2020 Parallel Shock Experiment Configuration:



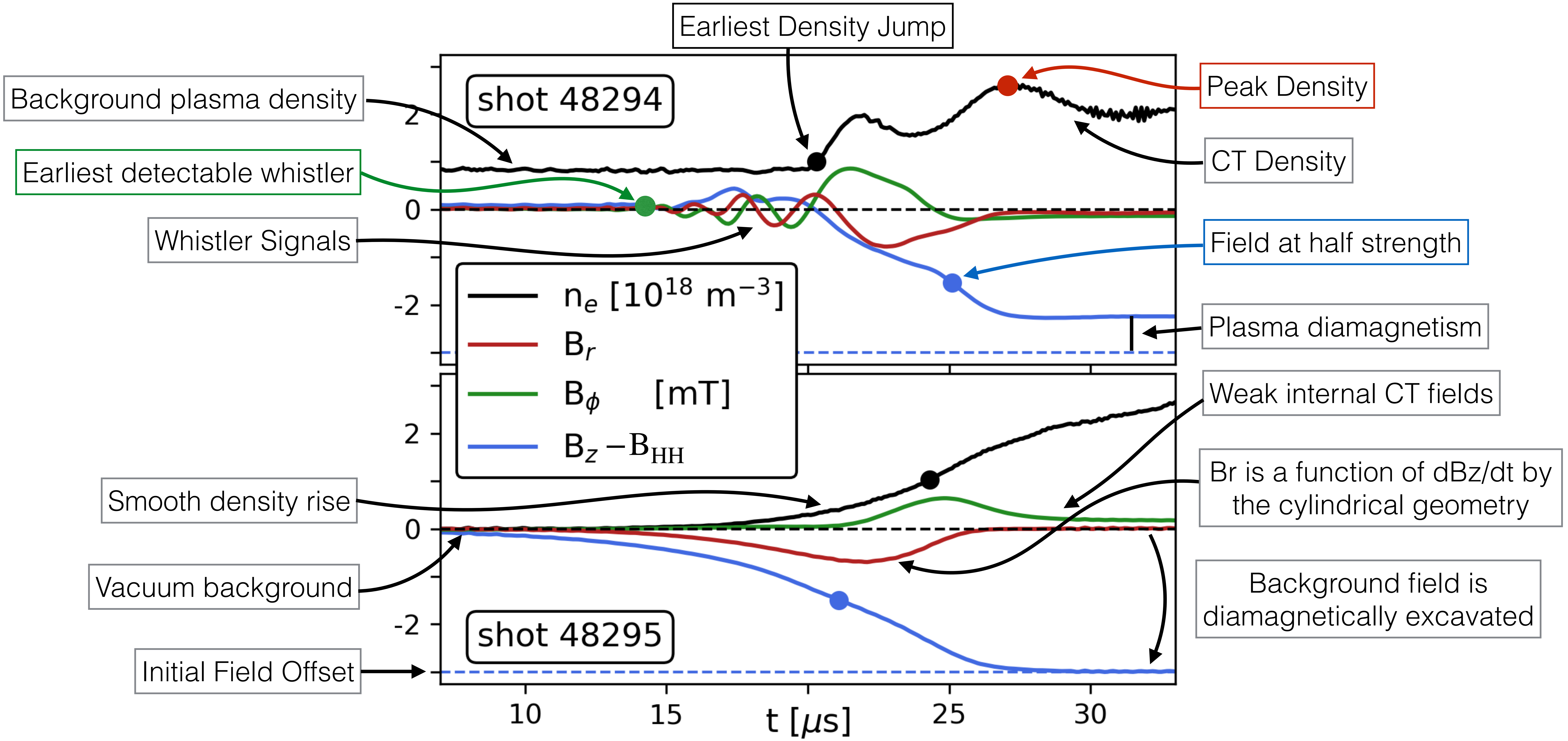


Primary Scan:

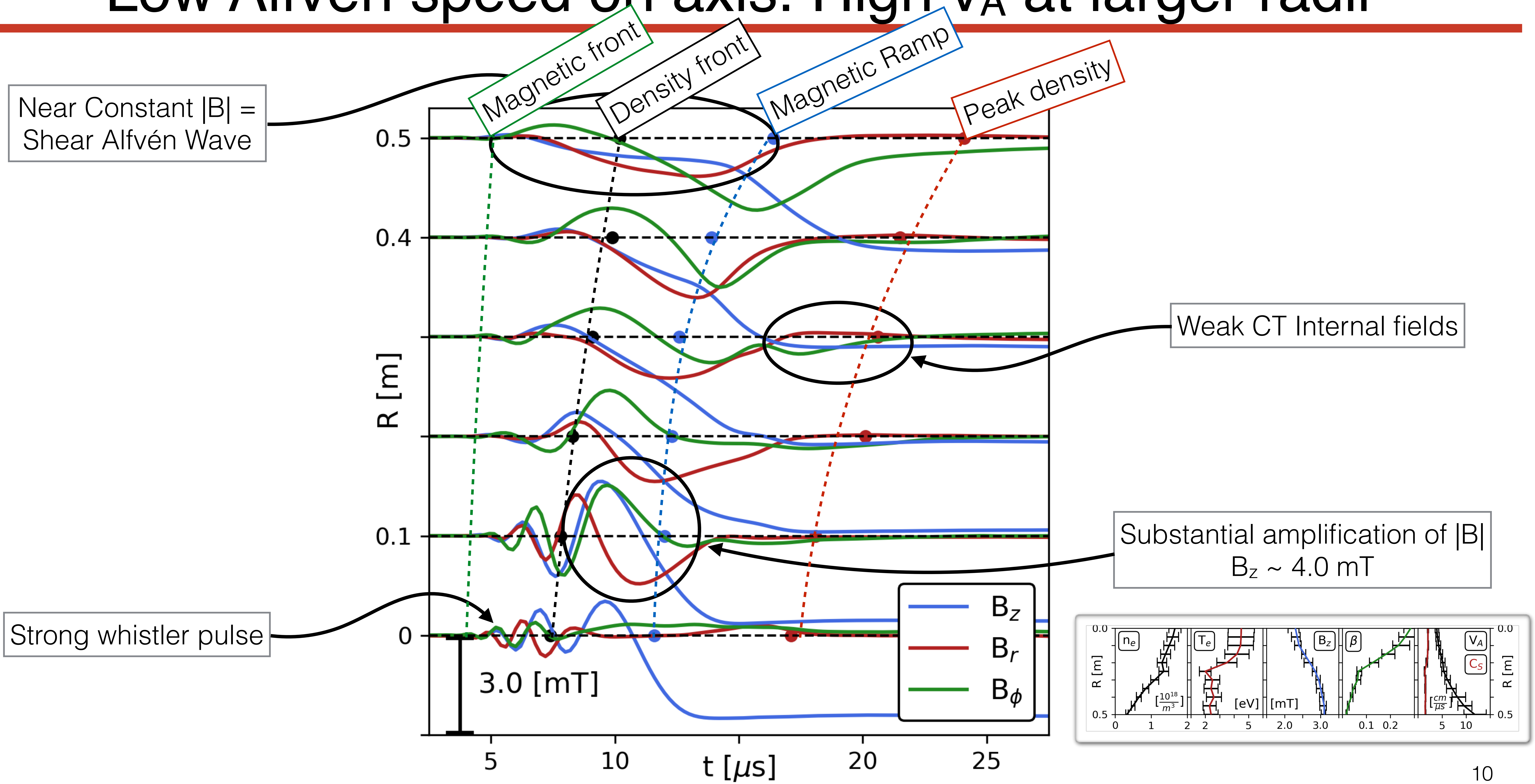
$$n_e = 1.6 \cdot 10^{18}\ \mathrm{m}^{-3} \qquad B_z = 3.0\ \mathrm{mT} \qquad v_{CT} \simeq 1$$

$$d_i = \frac{c}{\omega_{pi}} = 0.18\ \mathrm{m} \qquad \rho_i = \frac{v_{thi}}{\omega_{ci}} = 0.13\ \mathrm{m} \qquad v_A = 4$$

Vacuum vs Plasma comparison: Whistlers appear upstream in plasma



Radial View:
Low Alfvén speed on axis. High v_A at larger radii

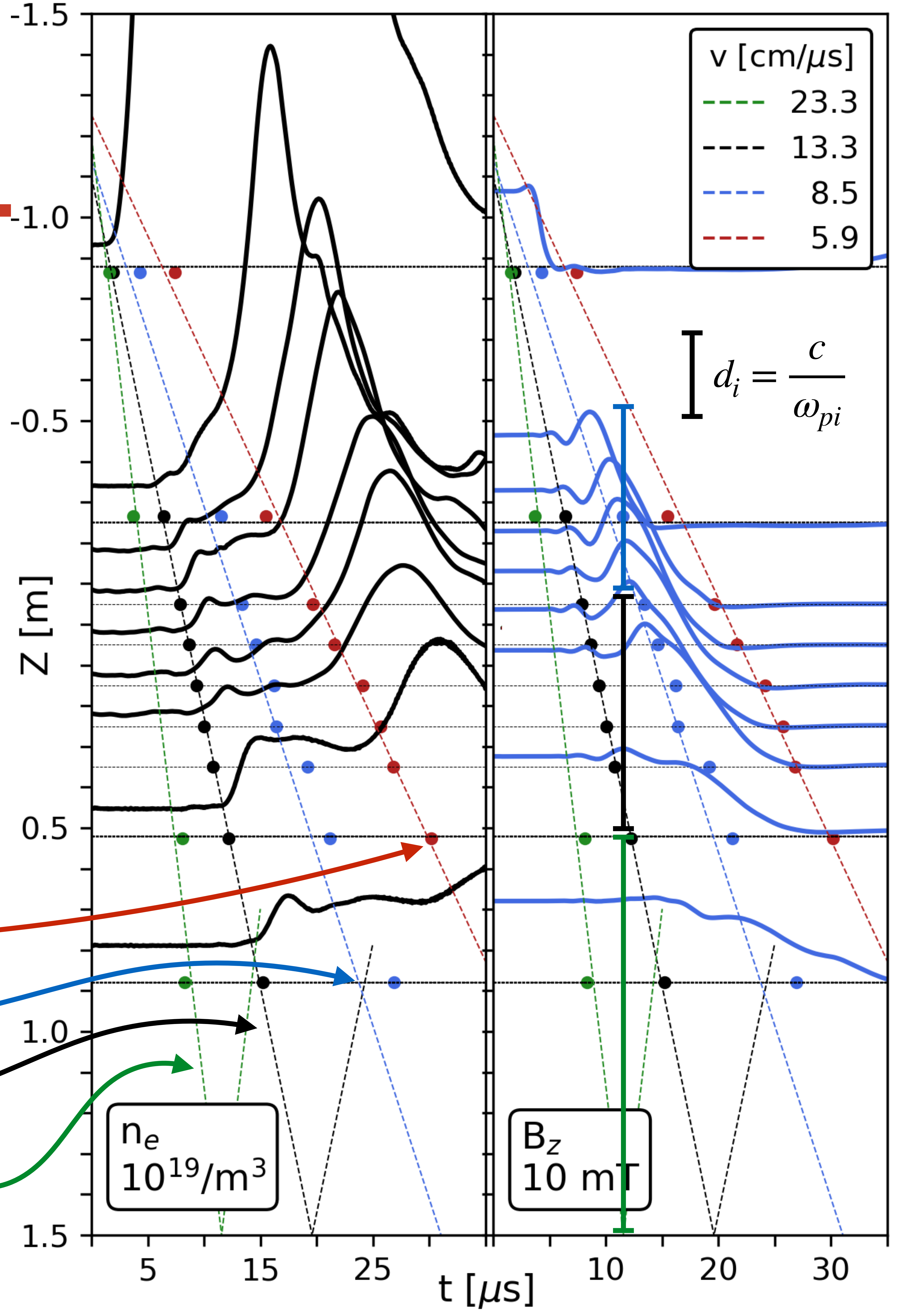


Axial View: Multiple group velocities

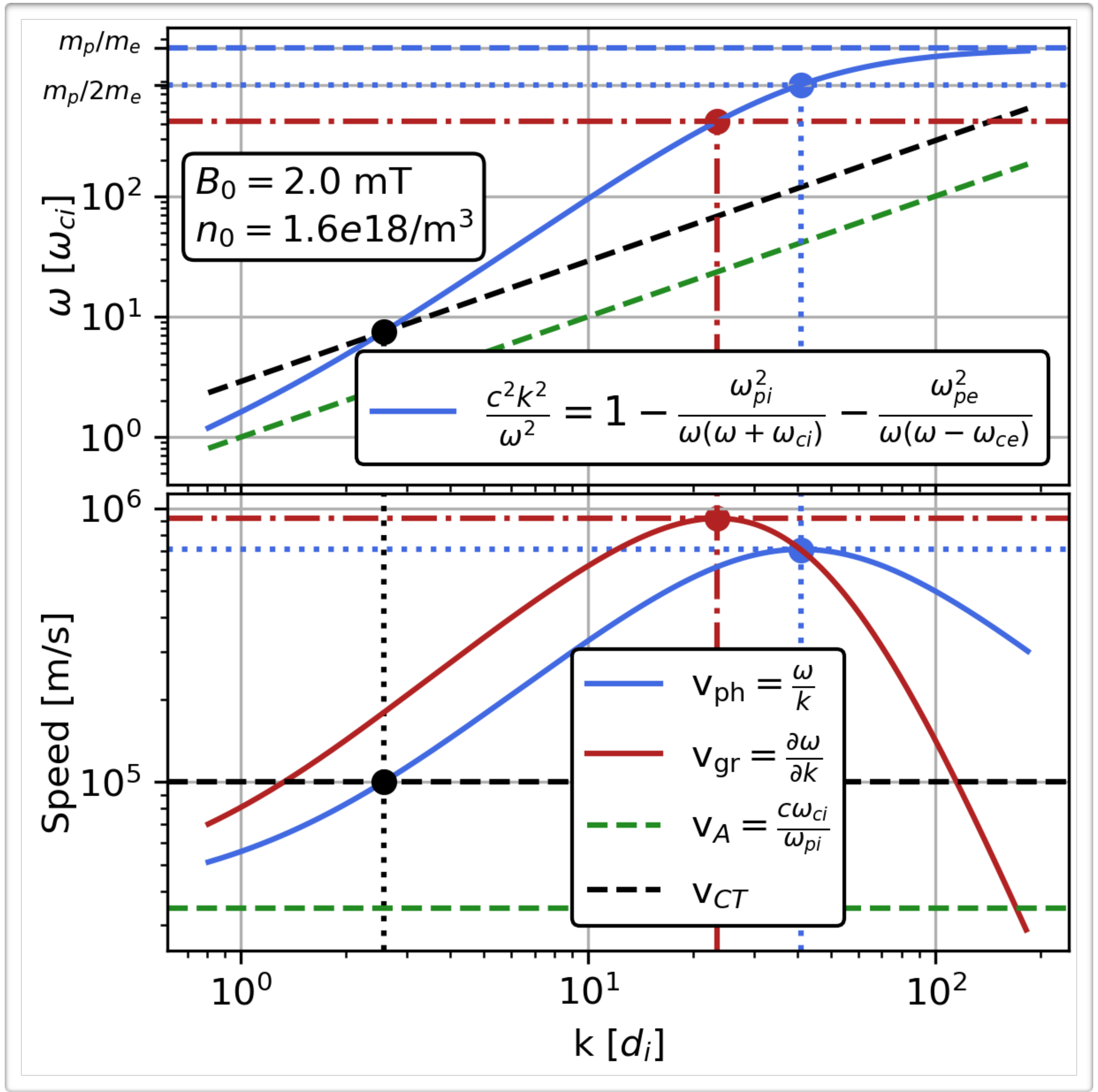
- Separation of several d_i between fronts
- Density jump occurs in ~1 d_i
- Magnetic Ramp M_A ~ 2

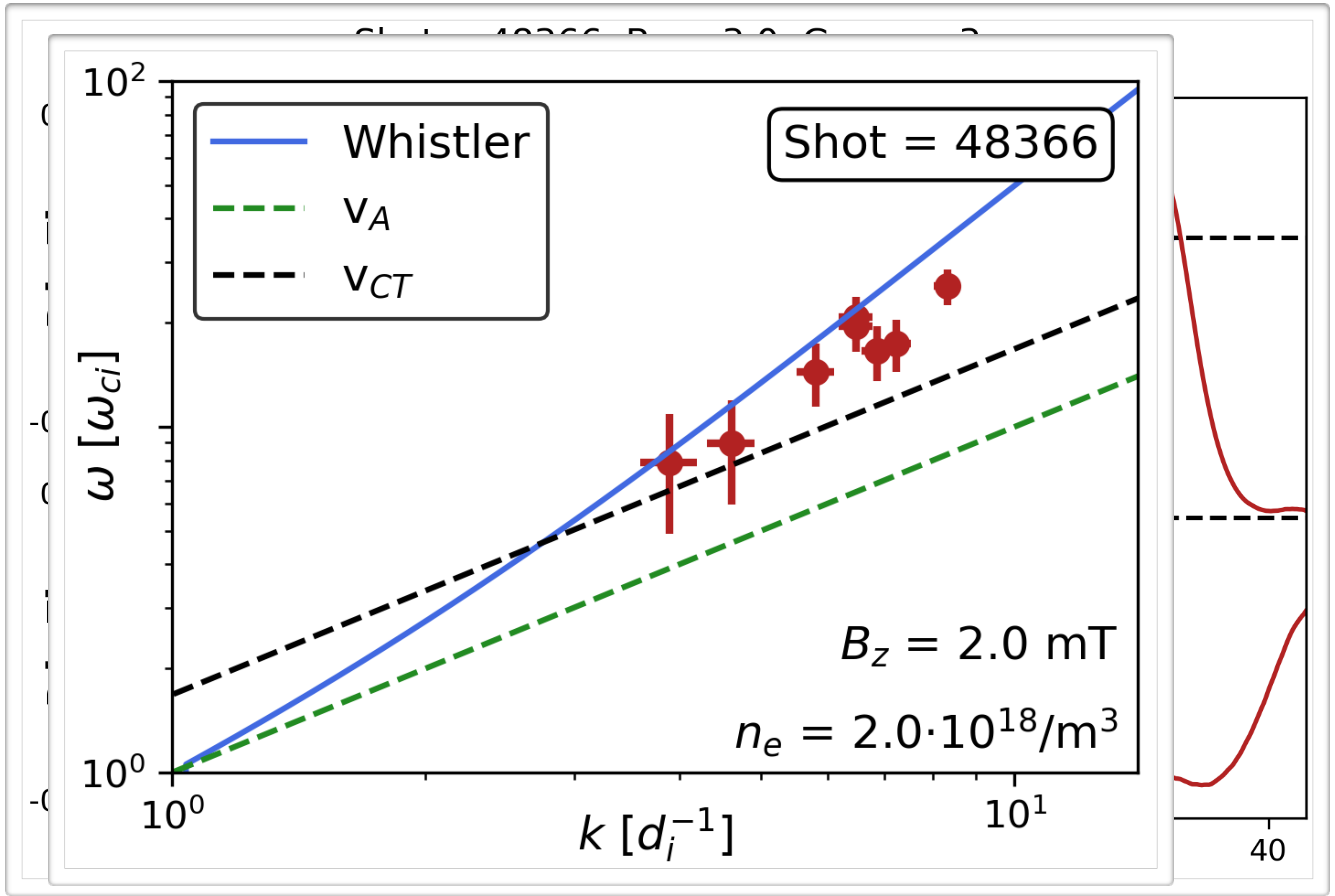
$$d_i = 18 \text{ cm}$$

$$f_{ci} = 35 \text{ kHz}$$

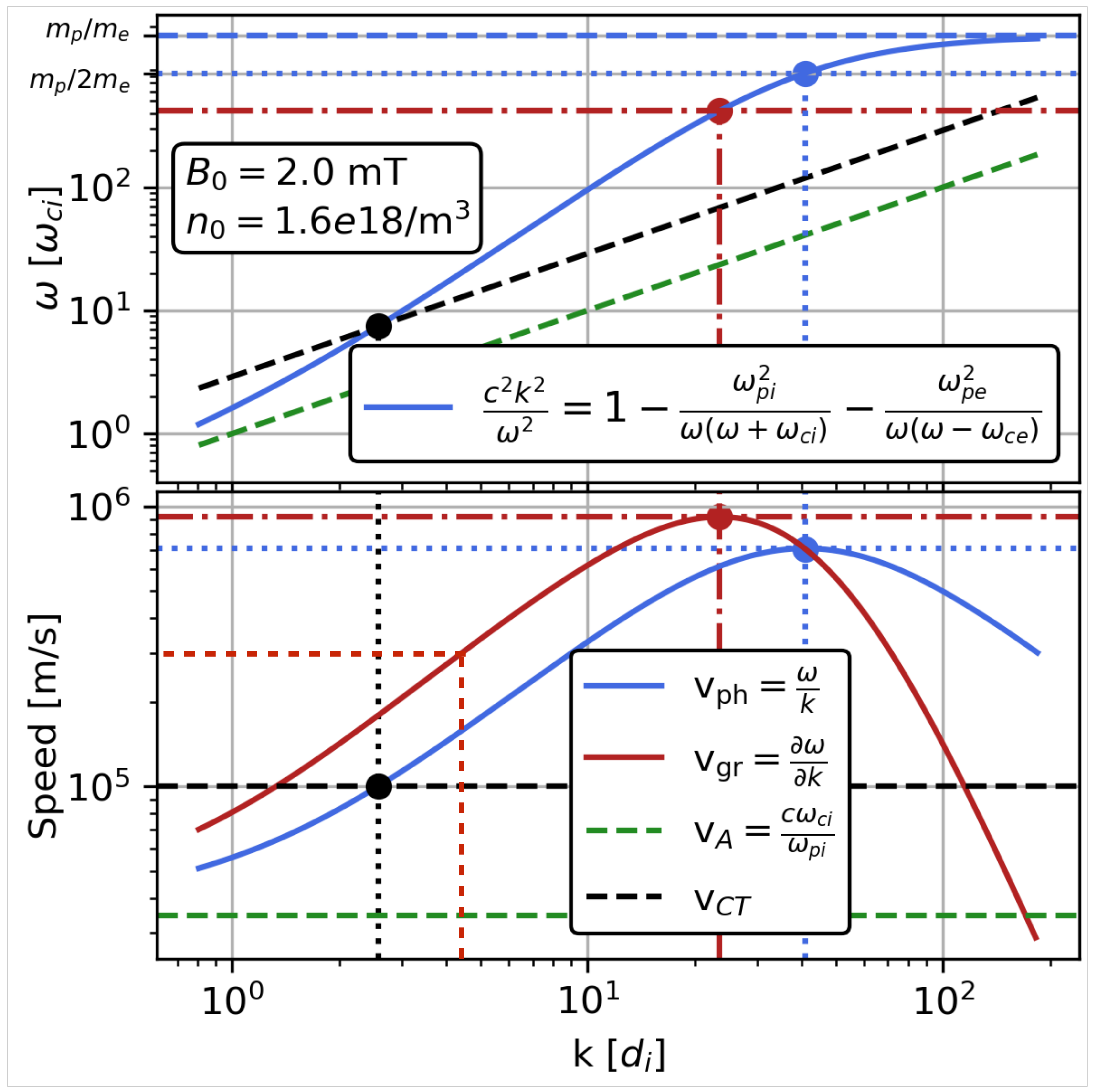


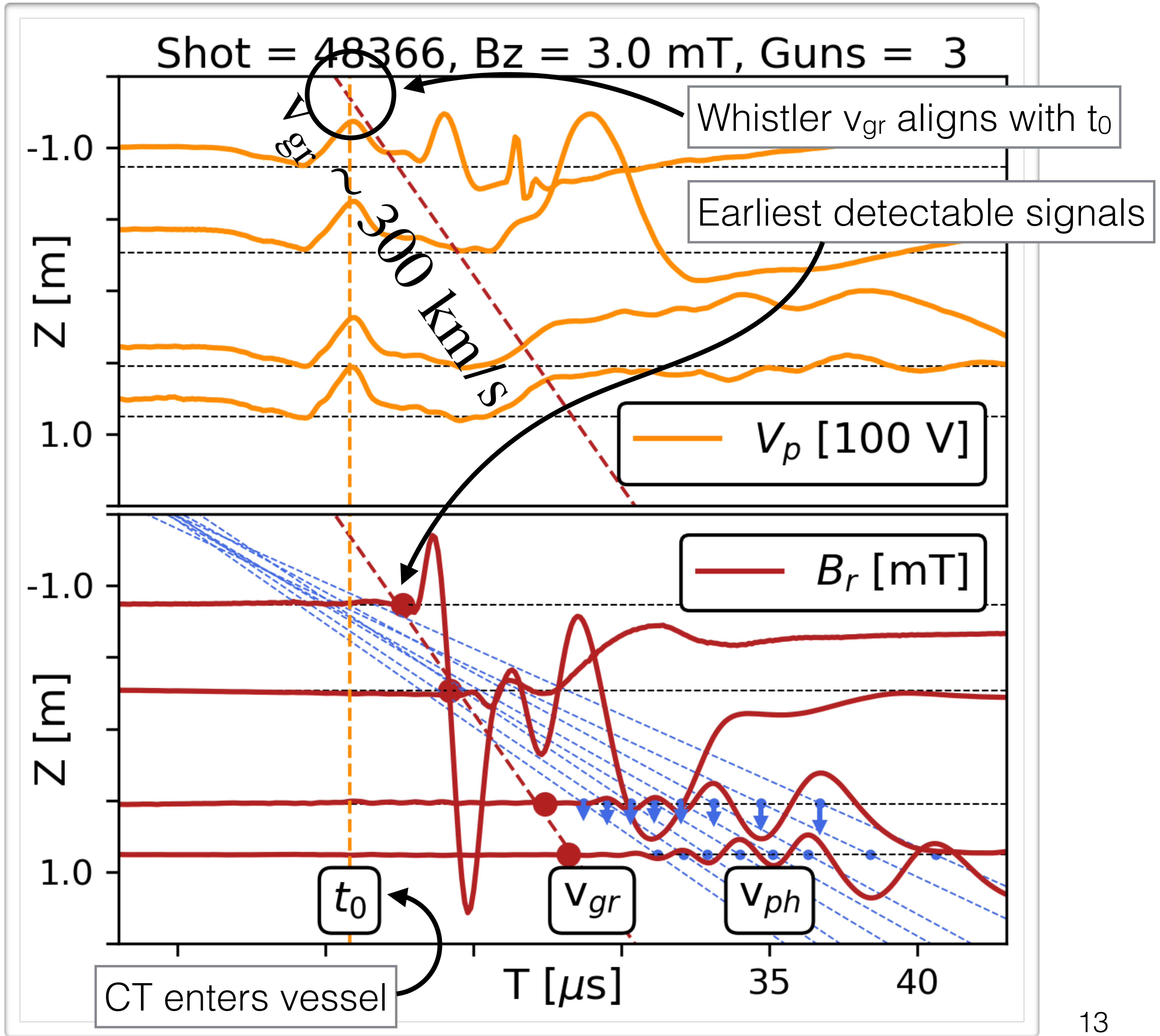
B_r and B_ϕ fluctuations are right hand polarized, V_{ph} agrees with Whistler dispersion



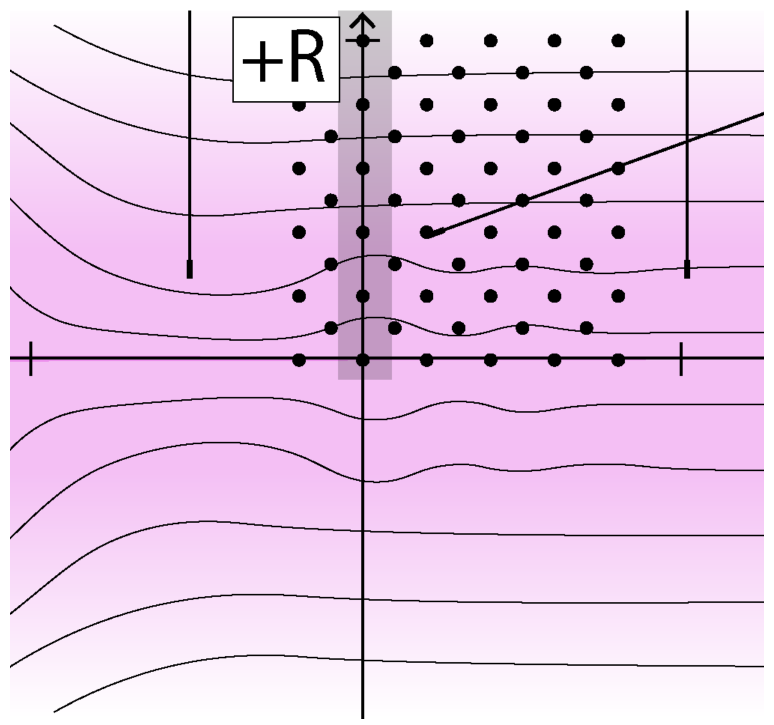


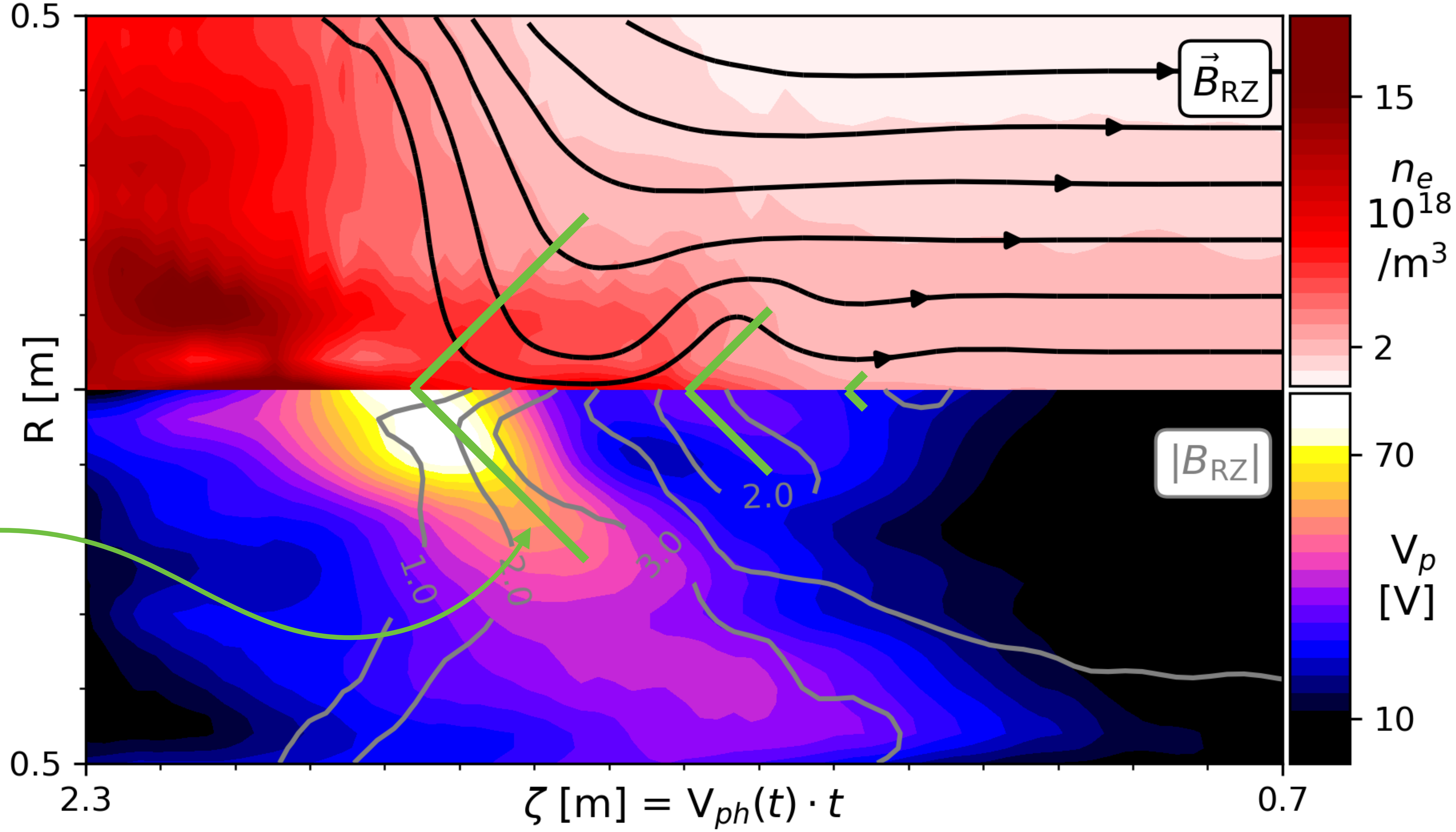
Group velocity indicates waves are from injection into vessel





Can use phase velocities to reconstruct in 2D





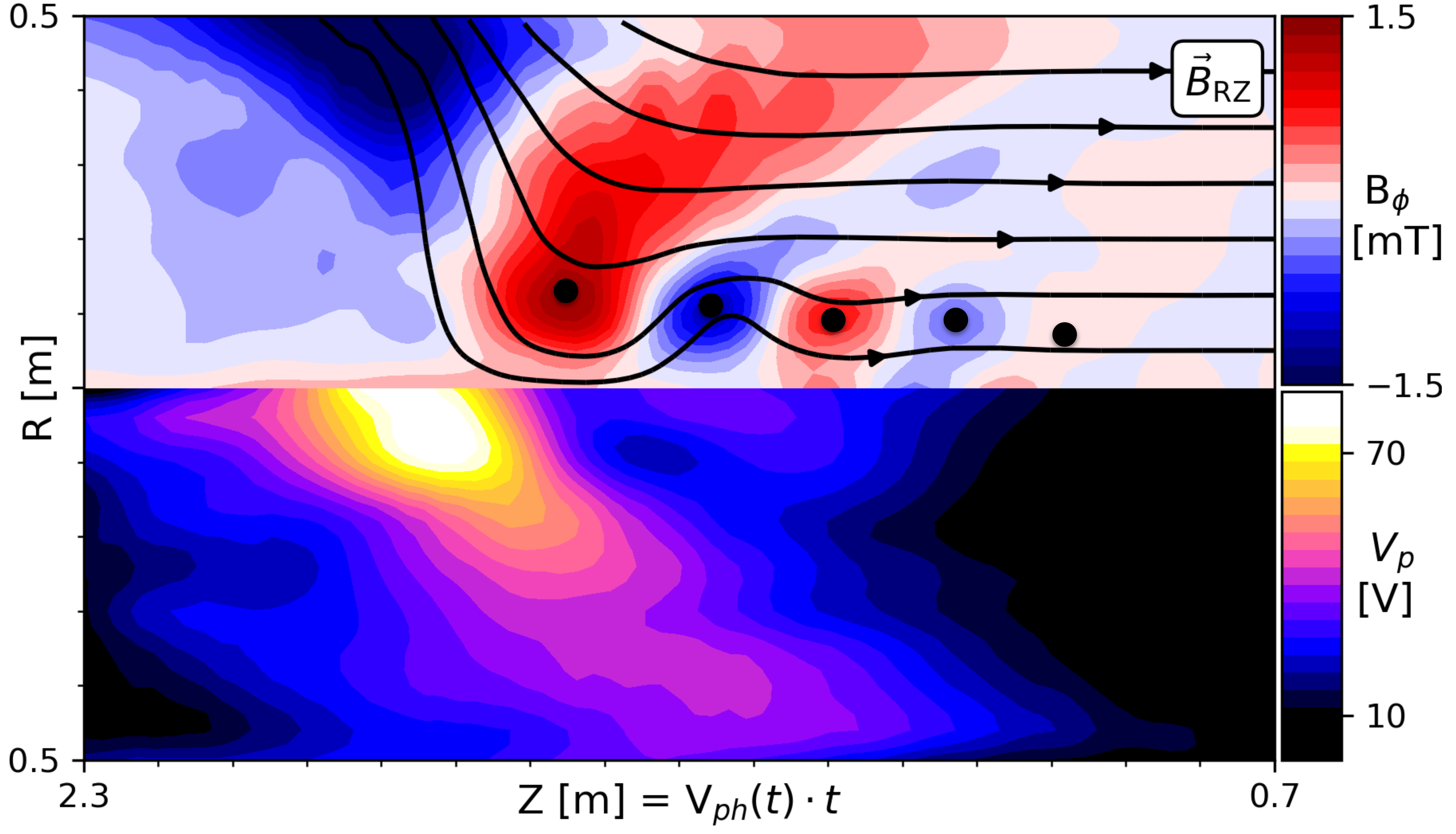
V-shaped potential

$$\frac{m_i v^2}{2} = q_e V_p$$

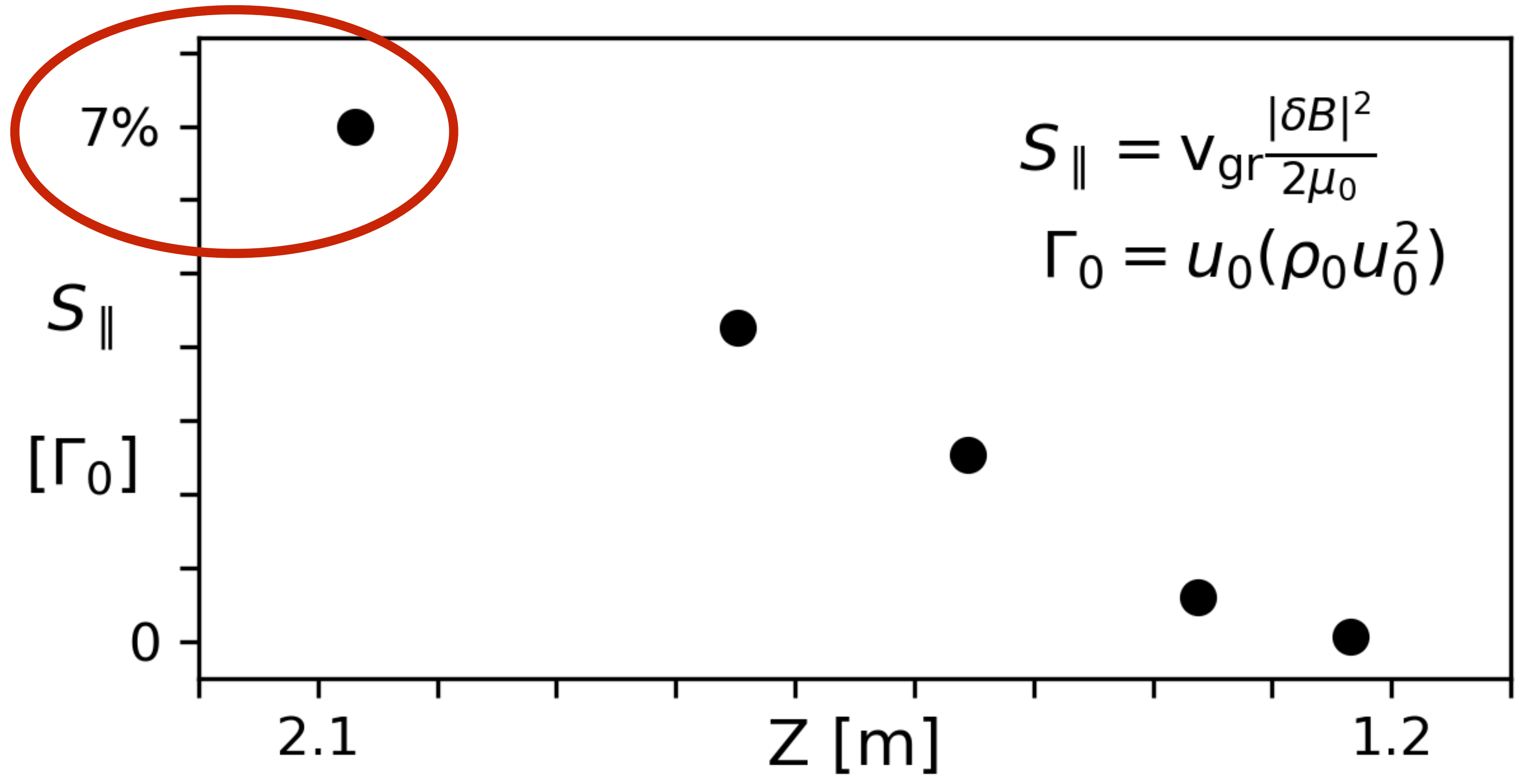
52 eV @ 100 km/s

Taylor hypothesis to real space is imperfect if: $v_{ph} \neq v_{gr}$

The upstream directed Poynting flux is a small fraction of the ram energy flux $u\rho u^2$

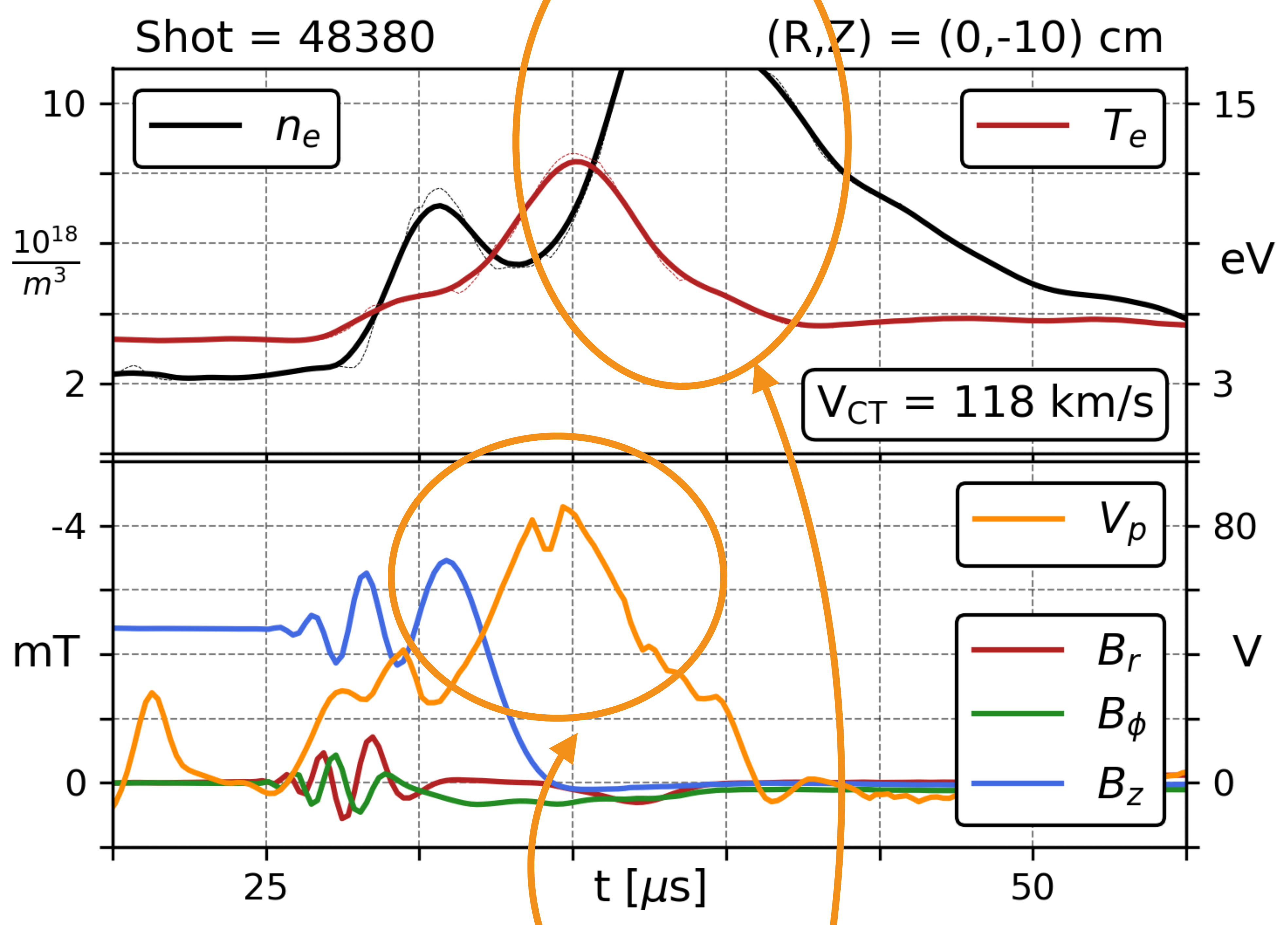


$$\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}$$

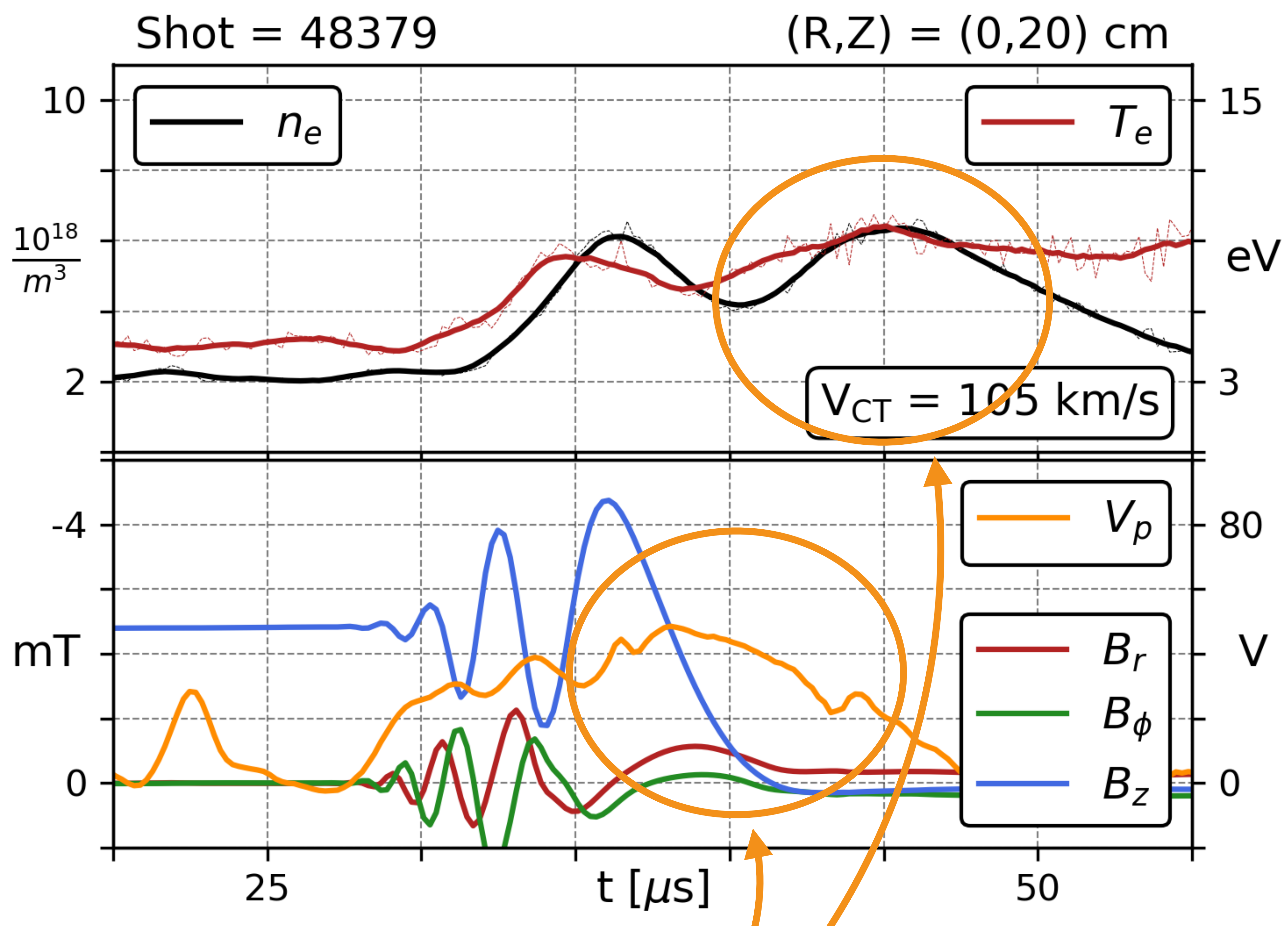


- Vp difficult to measure, so measurement error in E is large.
- Instead, calculate S from fluctuations in B and v_{gr}

CT expands continuously until it is no longer a piston



$\Delta Z = 30$ cm

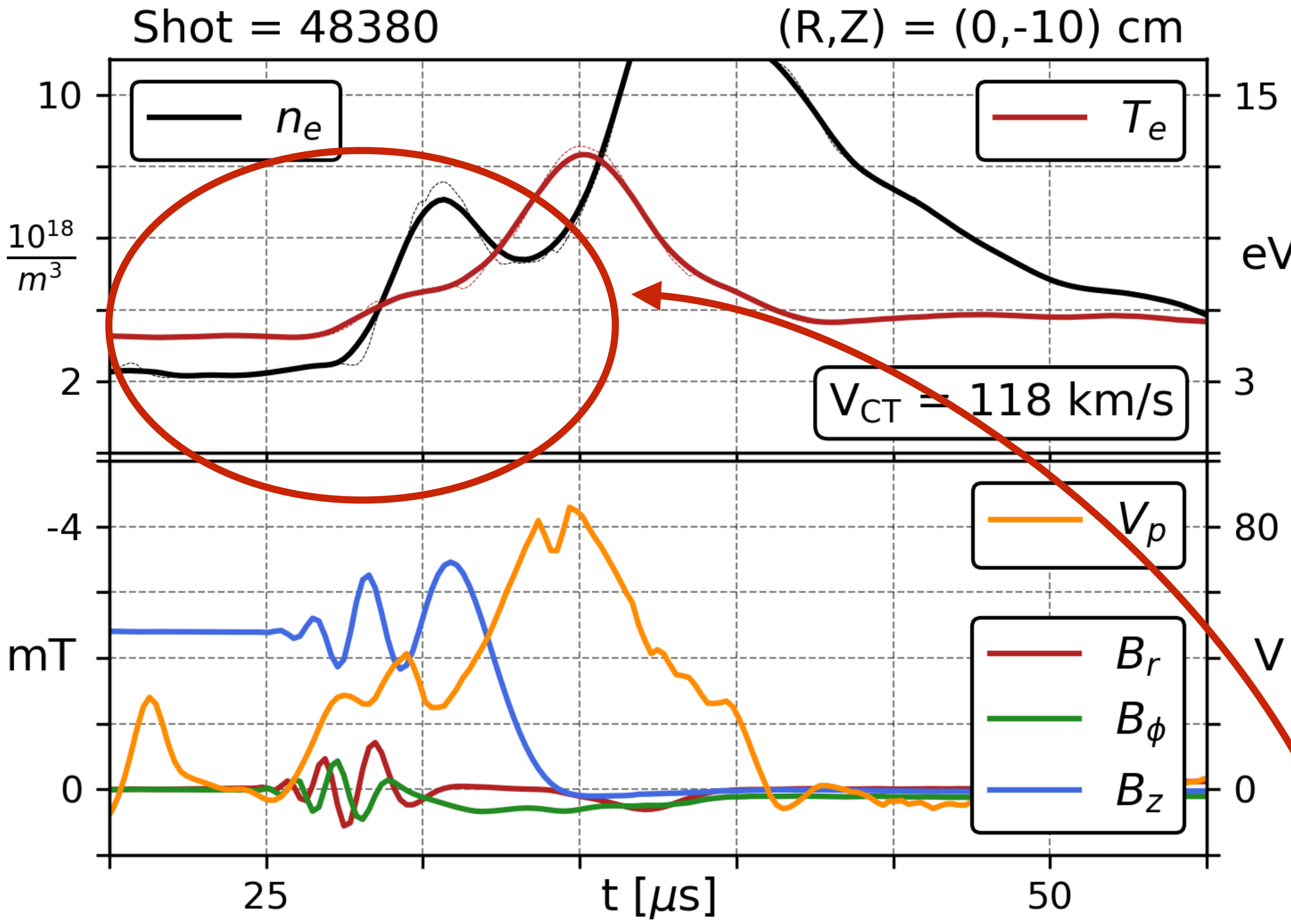


Potential structure at edge of density gradient

Plasma pressure driven piston disappears simultaneously with potential structure.

If the piston did not disappear, and if the leading potential jump kept growing, could be a reforming dispersive parallel shock.

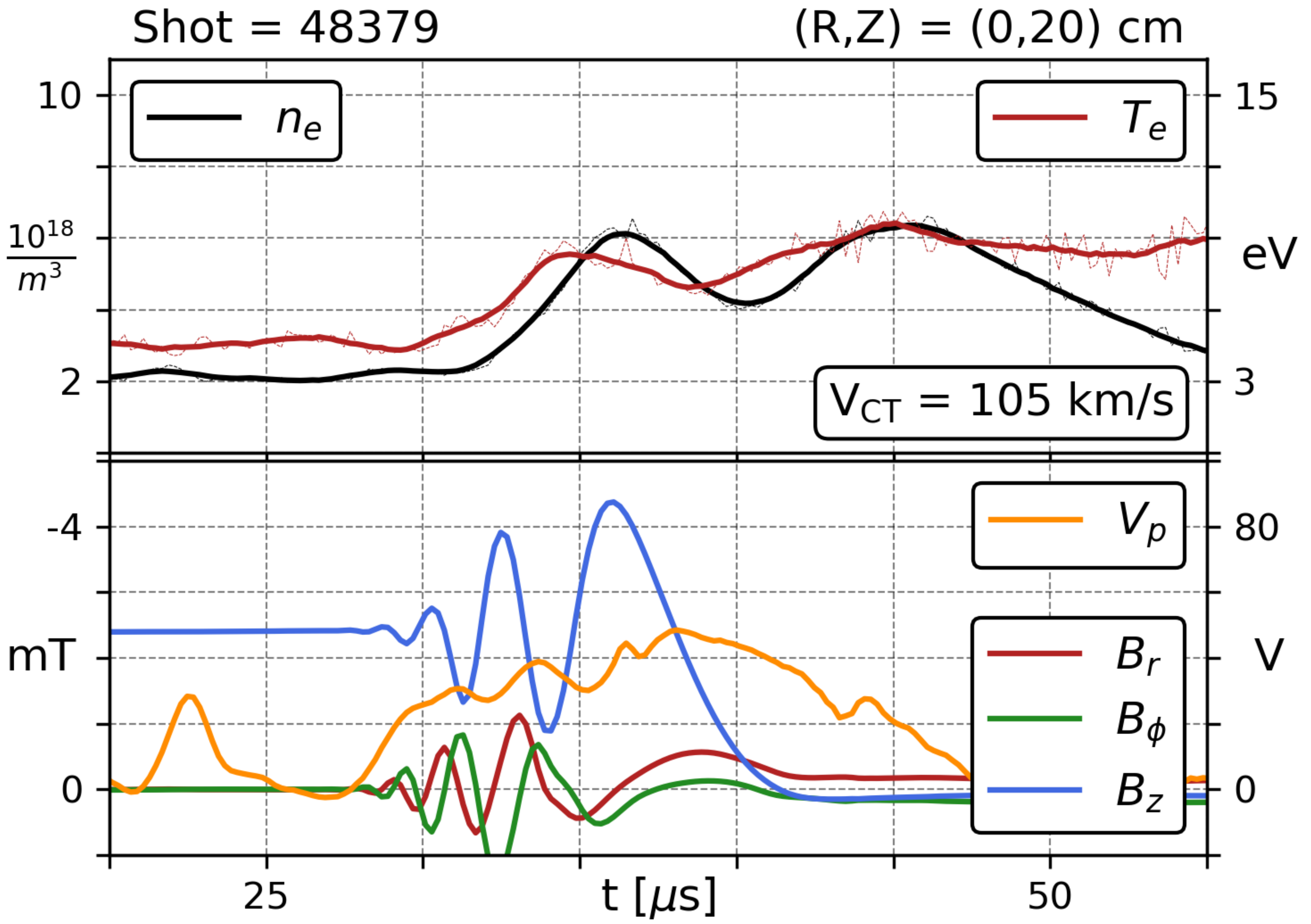
Comparing to Rankine-Hugoniot jump conditions is probably not appropriate, given cylindrical focusing



$$\Delta Z = 30 \text{ cm}$$

$$c_s = \sqrt{\frac{2T_e}{m_p}} \sim 30 \text{ km/s}$$

$$\mathrm{v}_A = \frac{B}{\sqrt{\rho\mu_0}} \sim 37 \text{ km/s}$$



$$\delta = \frac{\rho'}{\rho} = \frac{(\gamma+1)\ M^2}{(\gamma-1)\ M^2+2}$$

$$\frac{P'}{P} = \frac{\rho' T'}{\rho T} = \frac{2\gamma M^2 - (\gamma-1)}{\gamma+1}$$

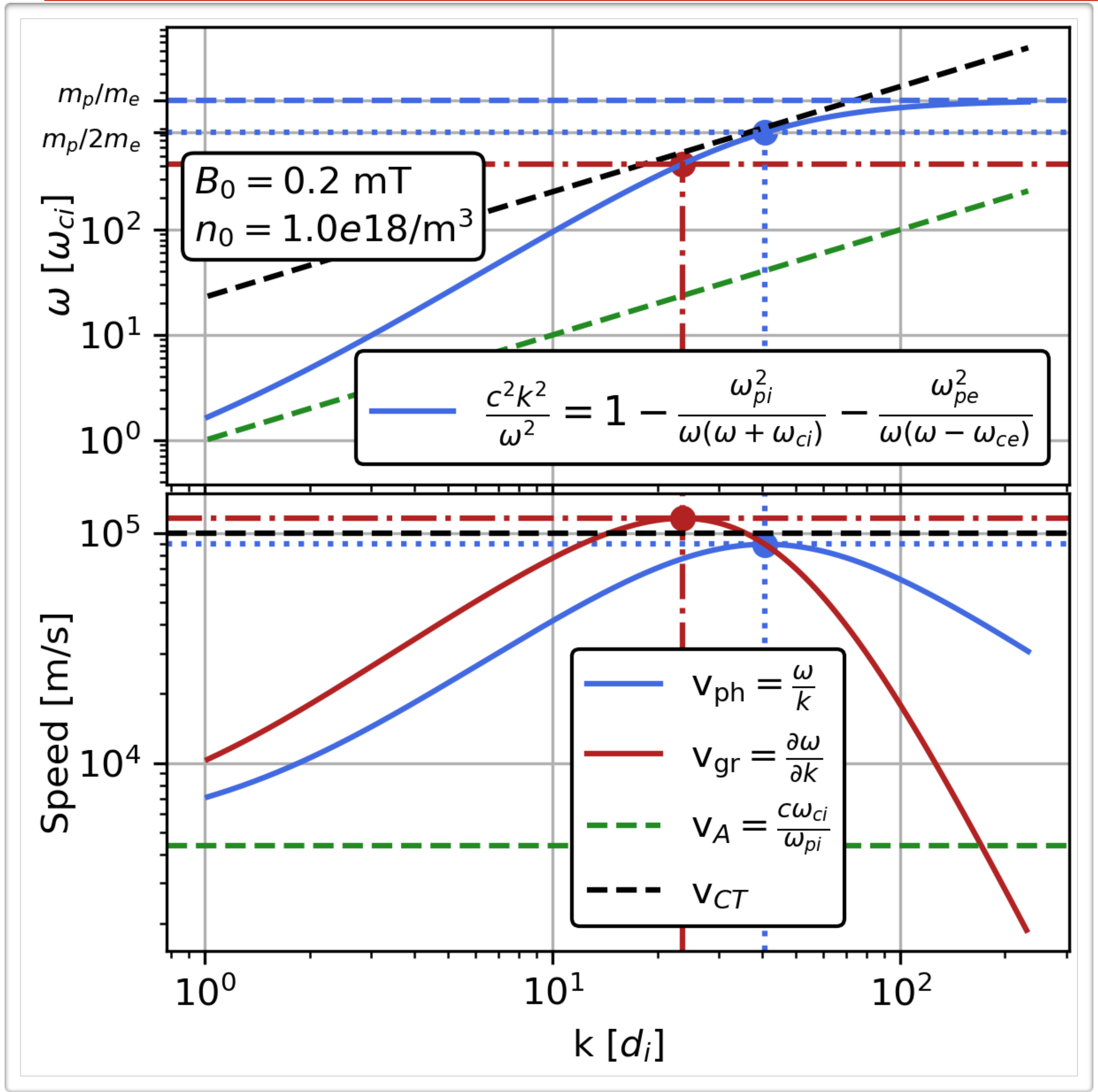
$$\xrightarrow[M_s = 4.0]{\gamma = \frac{5}{3}}$$

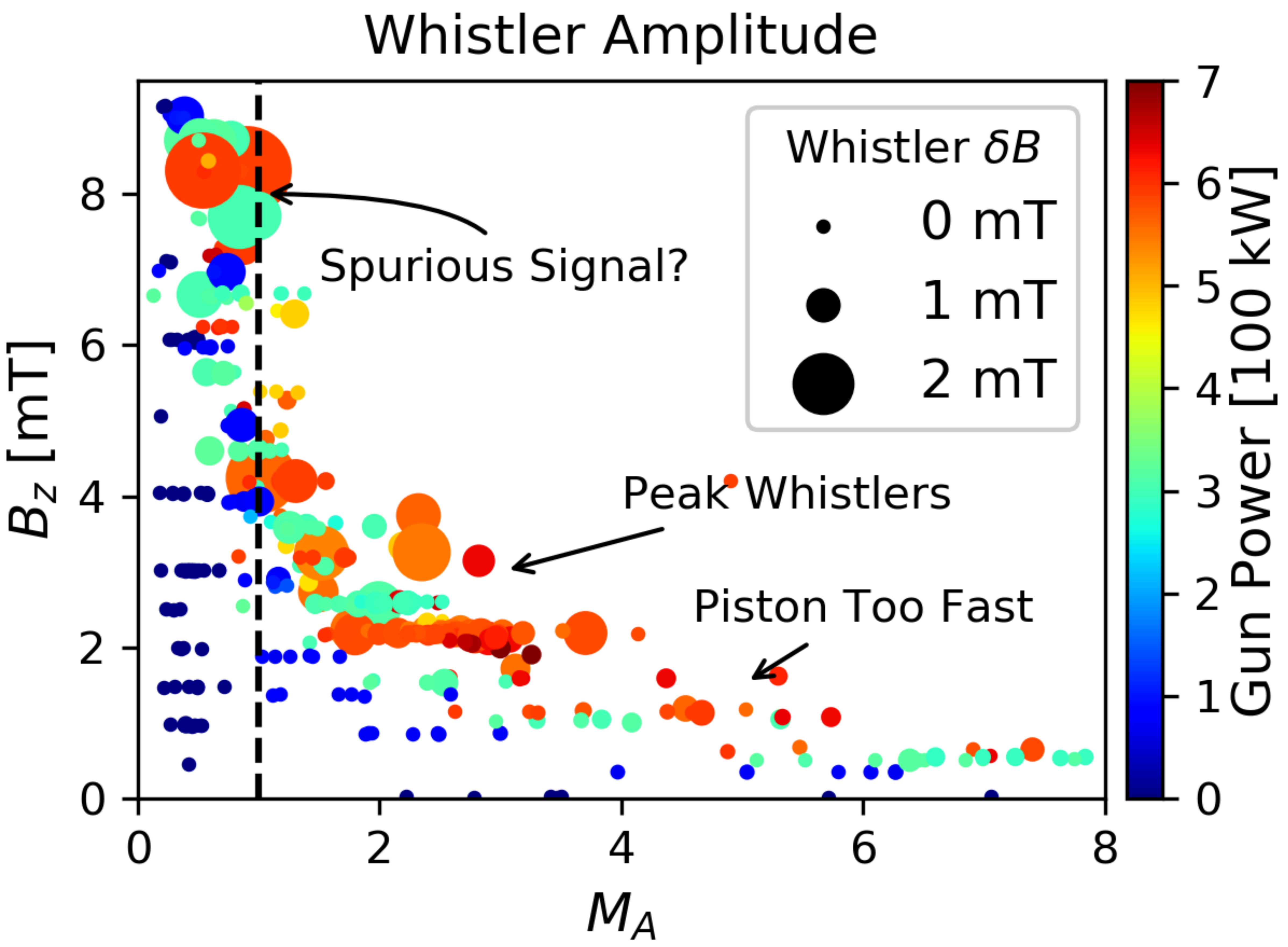
$$\frac{\rho'}{\rho} \sim 3.4$$

$$\frac{T'}{T} \sim 5.9$$

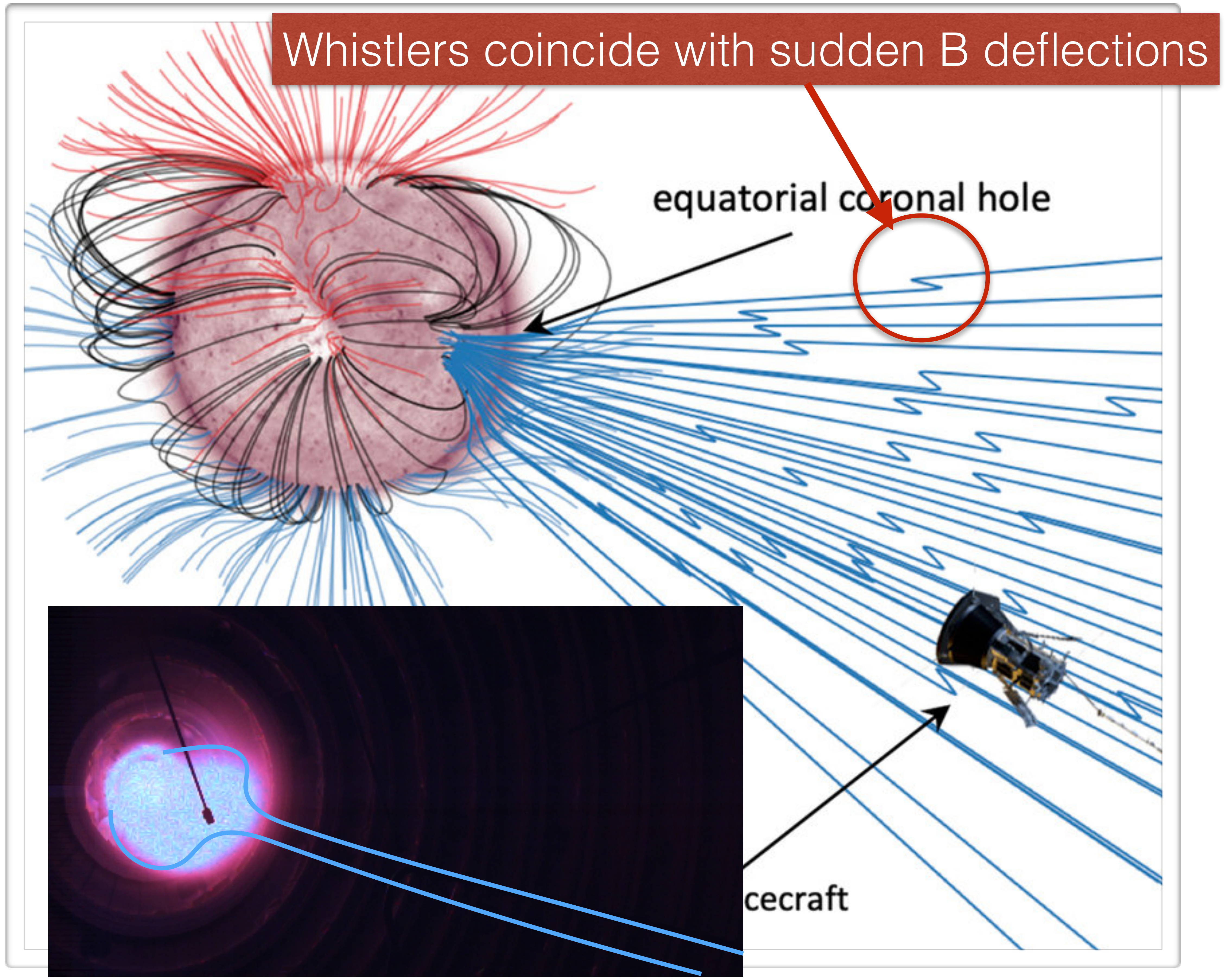
Peak measured density hits RH values

Explored a large parameter space. Only observed whistlers at moderate M_A





Connections to space physics: Whistlers around Switchbacks in the Solar Wind



Bale, S. et al., (2019). Highly structured slow solar wind emerging from an equatorial coronal hole. Nature. 576.

- "These waves may result from large velocity shears at the switchback boundaries, which cause the boundaries to be Kelvin-Helmholtz unstable."

Mozer, F.S. et al., (2020). Switchbacks in the solar magnetic field: their evolution, their content, and their effects on the plasma. The Astrophysical Journal, 246, 68.

- These whistlers may be important for scattering strahl electrons:

$$\omega - \mathbf{kV} = \frac{n\Omega_{ce}}{\gamma}$$

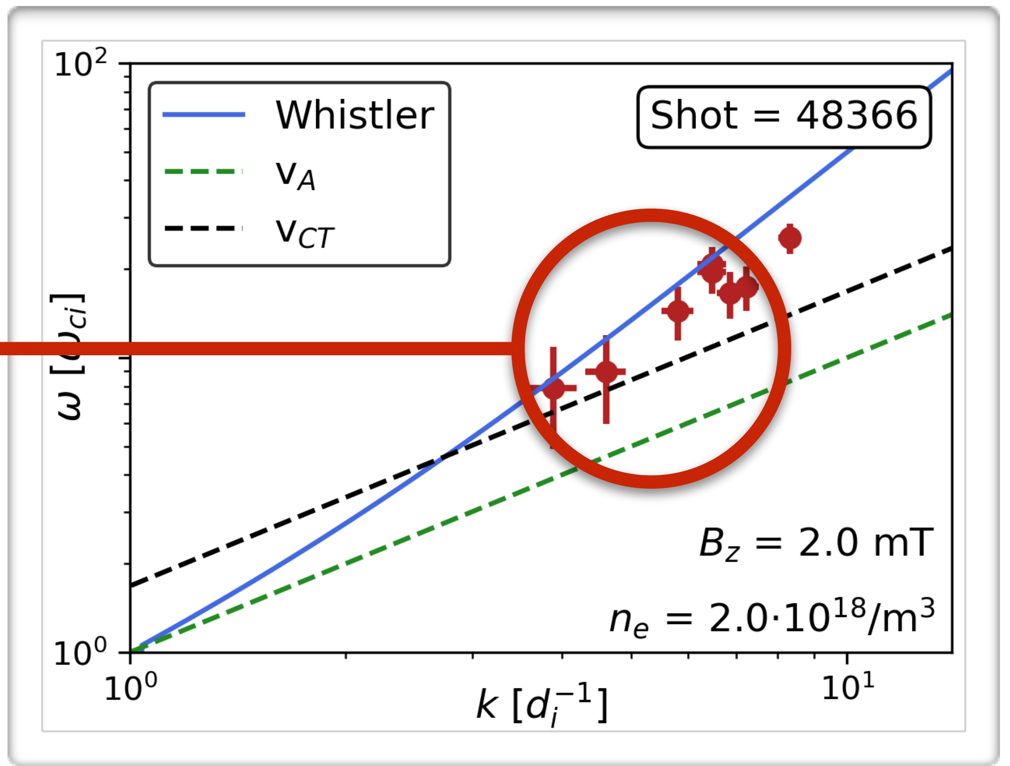
Agapitov, O.V. et al., (2020). Sunward-propagating Whistler Waves Collocated with Localized Magnetic Field Holes in the Solar Wind. The Astrophysical Journal, 891(1)

Whistler heating is important in space. Did not observe resonant electron heating.

$$\omega - \omega_{ce} = \mathbf{k} \cdot \mathbf{v_e}$$ Resonance condition for collisionless electron cyclotron damping

$$\omega \sim 20\, \omega_{ci}$$

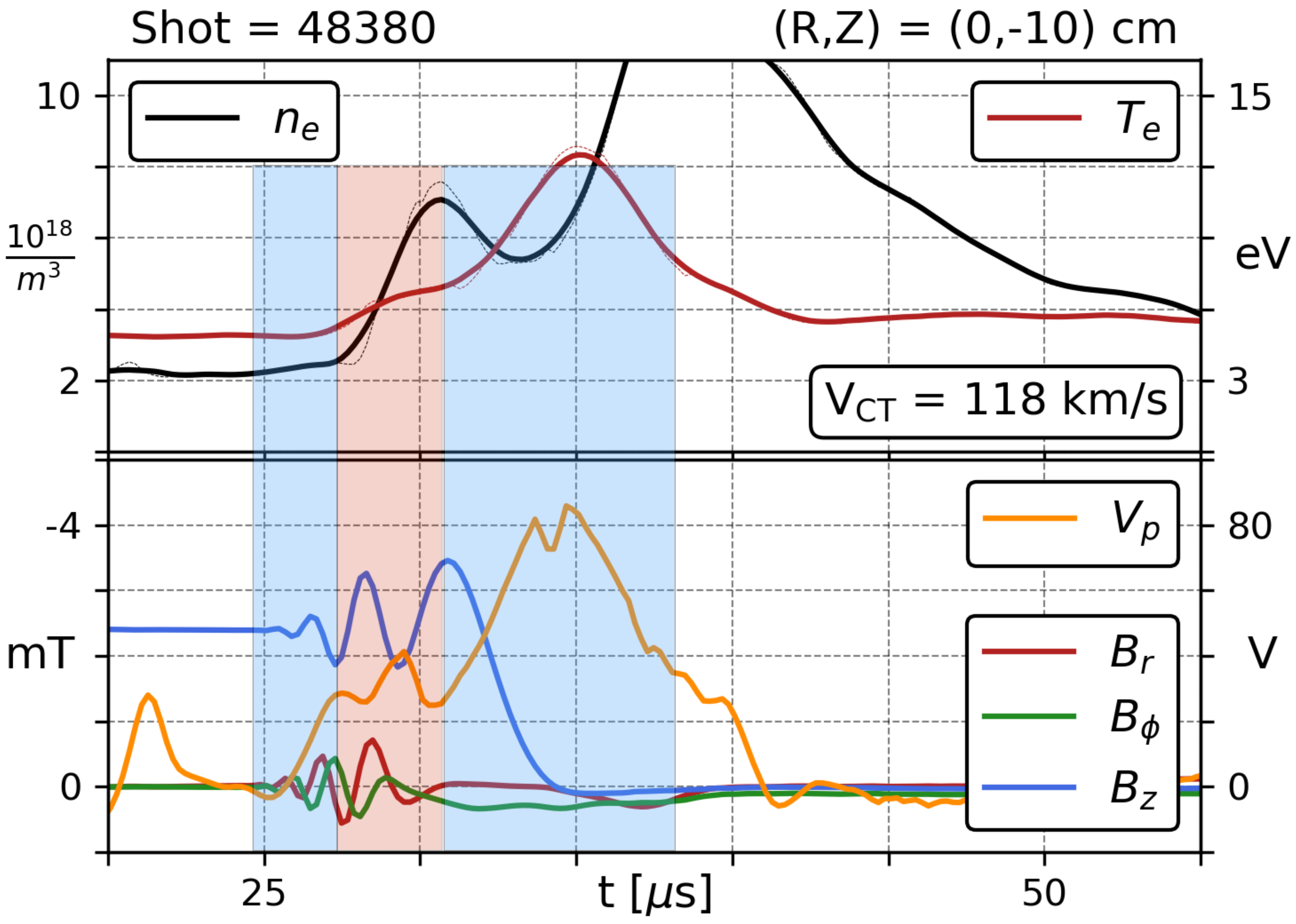
$$k_{\parallel} \sim 7$$



$$\frac{\omega - \omega_{ce}}{k_{\parallel}} \sim -9000 \text{ km/s}$$

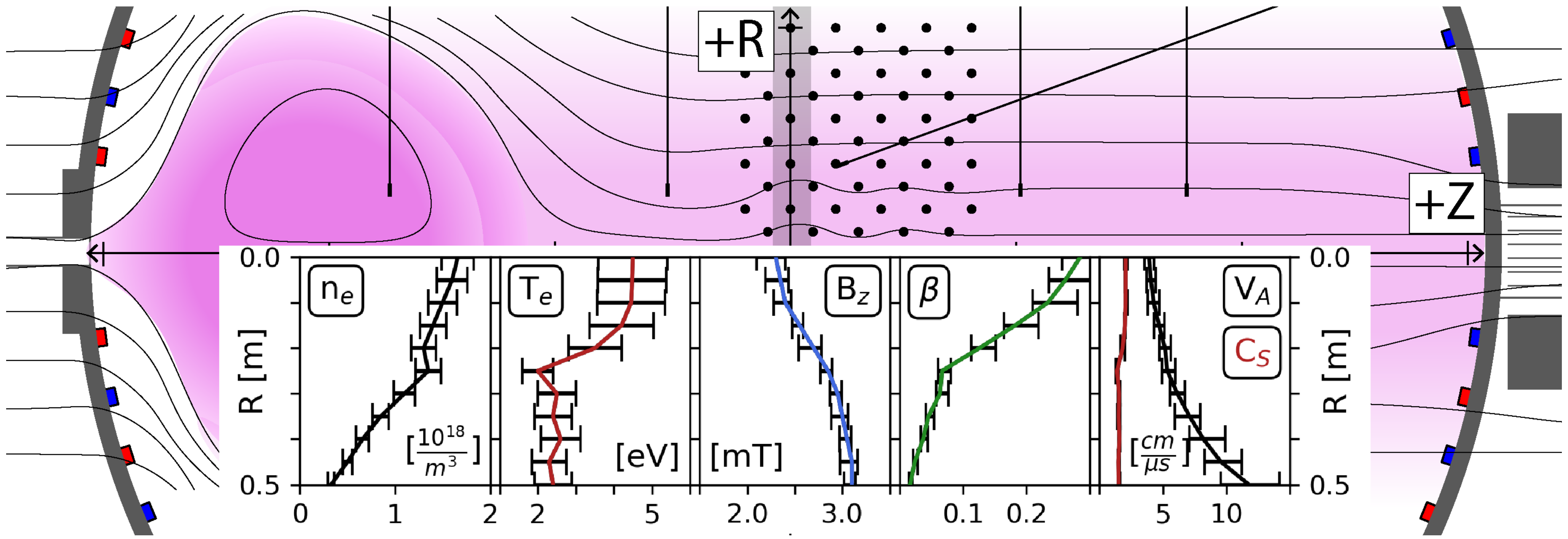
$$v_{the} = 1000 \text{ km/s}$$

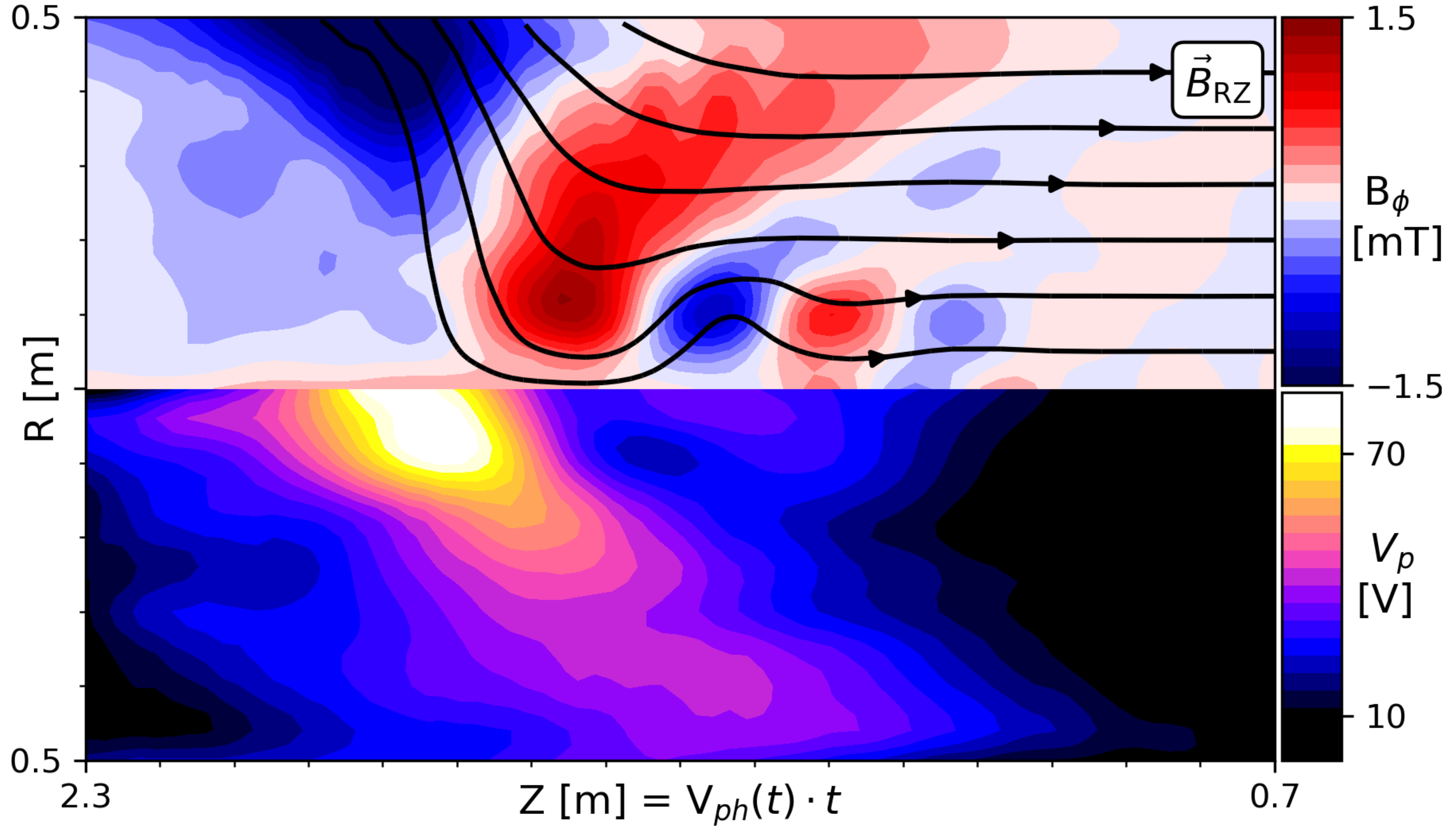
With the collisional Maxwellian background, there are probably zero resonant electrons.



Conclusions

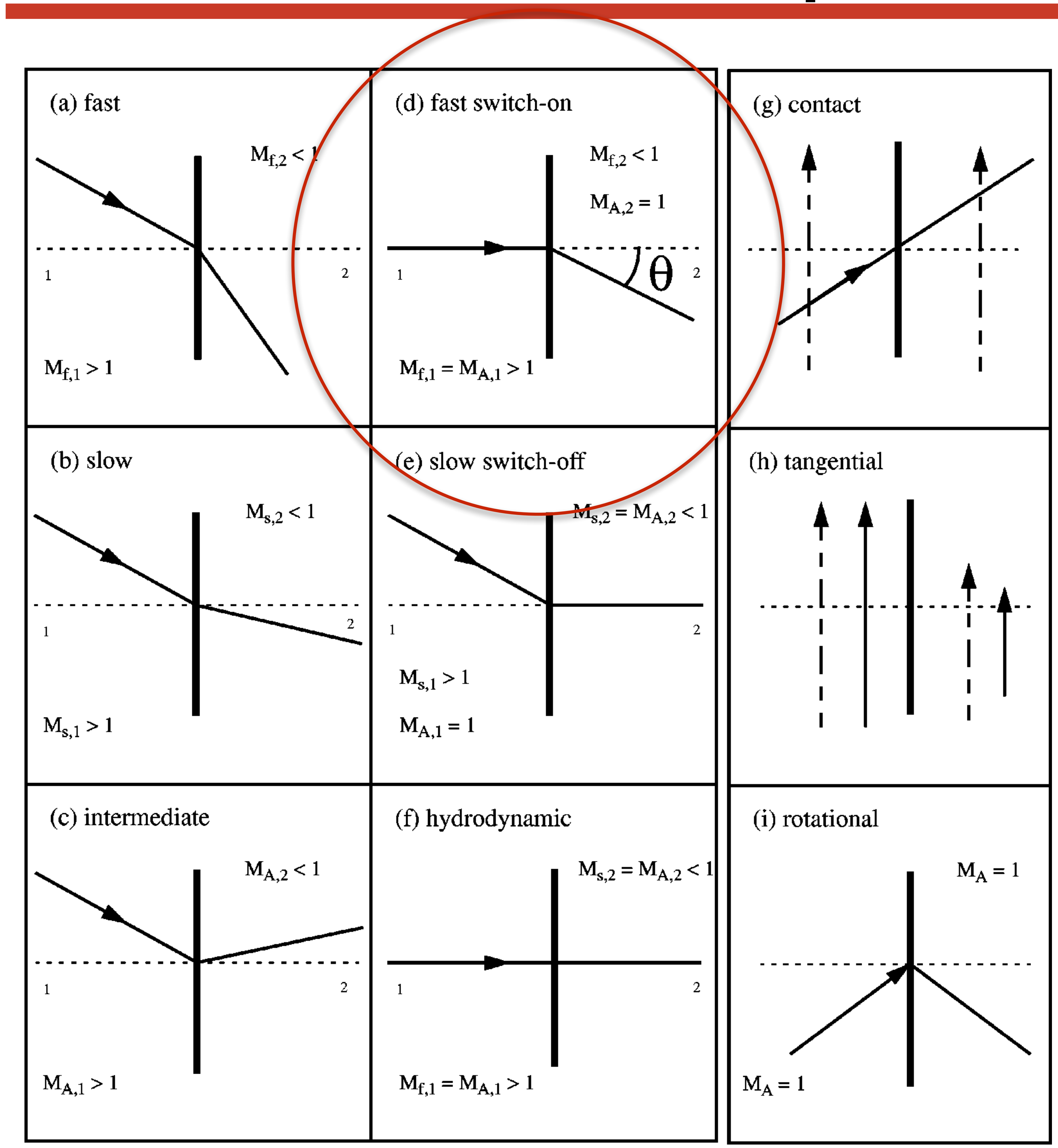
- Observed formation of a whistler mediated parallel shock
- If the piston continued, we might see the formation of a second potential structure strong enough to independently reflect ions, i.e. a detached reforming shock





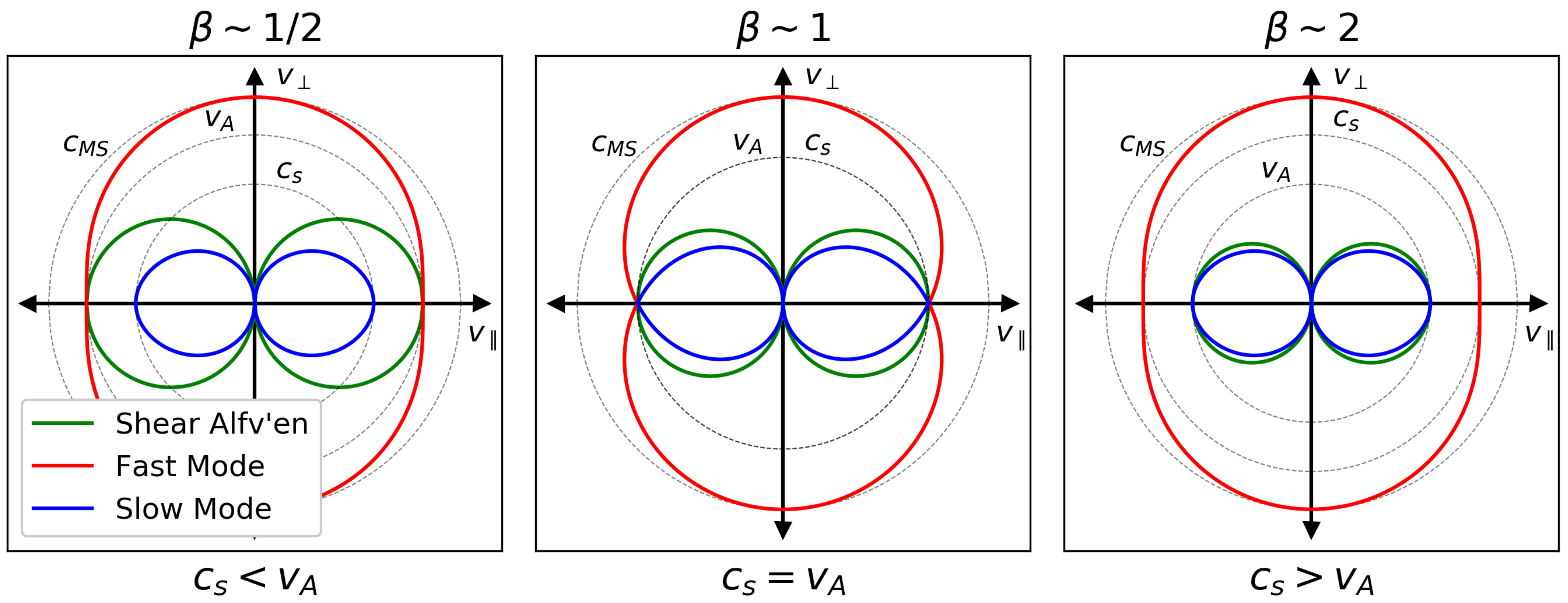
Back-up Slides

Primary Motivation: Does MHD predict the structure of Lab Shocks?



De Sterck, Low and Poedts, Complex magnetohydrodynamic bow shock topology in field-aligned low-b flow around a perfectly conducting cylinder, Physics of Plasmas, Nov 1998, Vol 5 N 11

Friedrich Polar Diagram of Phase Velocity $v_p = \omega/k$ of MHD Waves



This is particularly unclear for 'parallel' shocks:

- SLAMS
- Reformation
- Energy partition/Heating
- Energization

Unlike the perpendicular case, the parallel shock case has multiple shock solutions.

Friedrich Polar Diagram of Phase Velocity $v_p = \omega/k$ of MHD Waves

Example Experiment 1: Historic Pulsed Power Parallel Shock Experiments

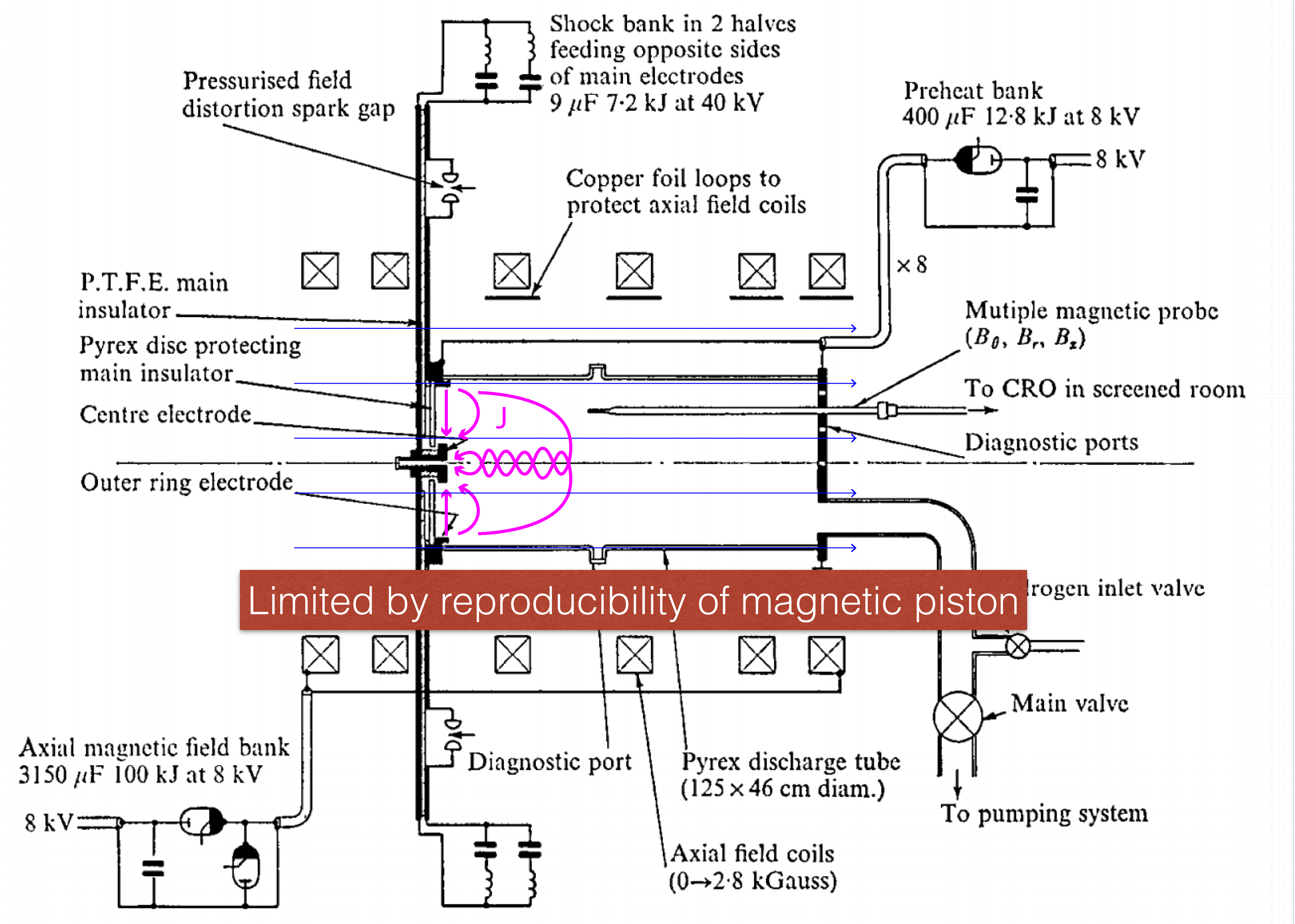
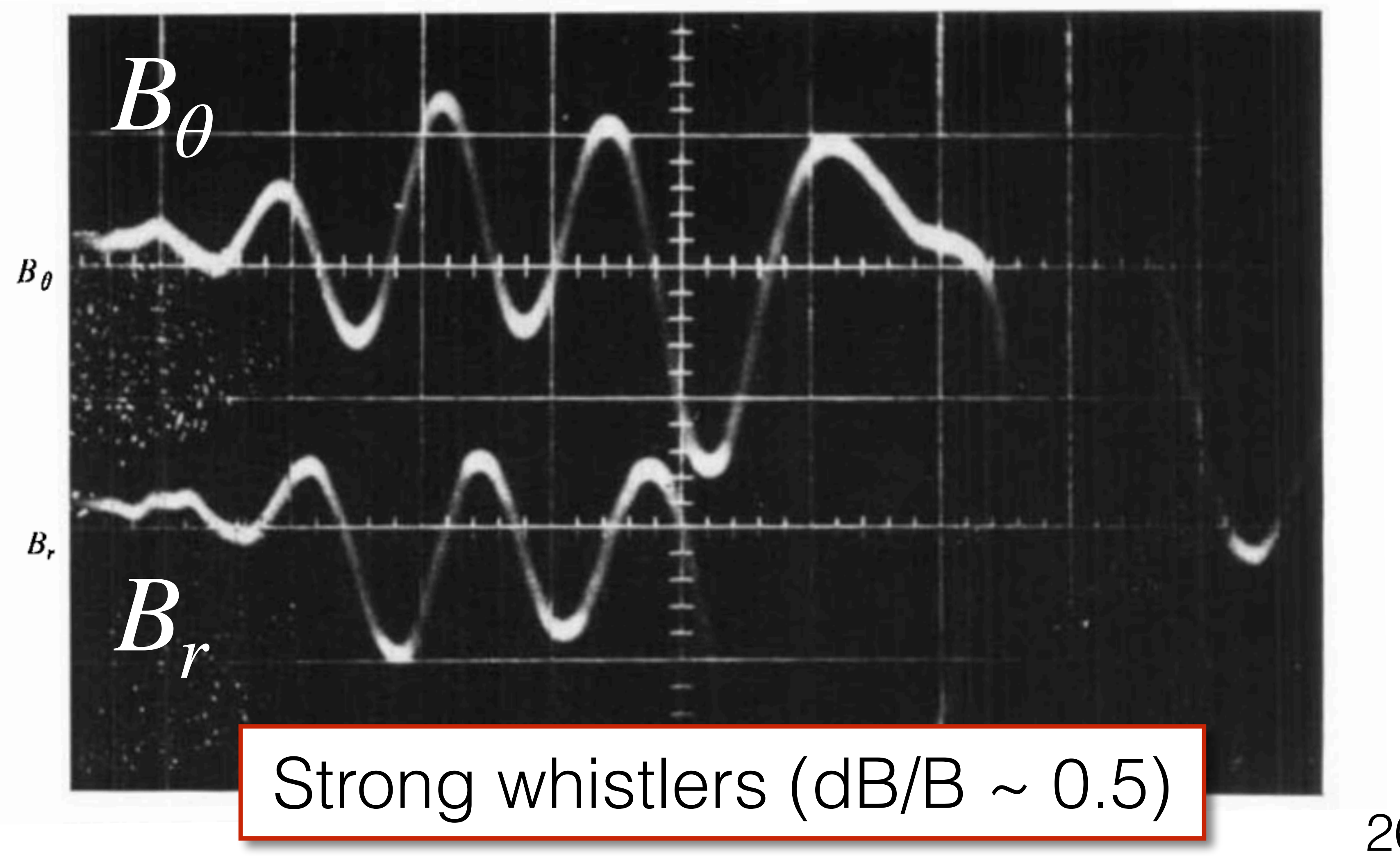


FIGURE 3. Schematic of the Charybdis apparatus.

A.D. Craig and J.W.M. Paul, "Observation of 'switch-on' shocks in a magnetized plasma", *J. Plasma Physics* (1973), vol. 9, pp 161-186

	min	max	
n_e	4	8	$10^{20}/m^3$
T_e		1.3	eV
B_z	50	250	mT
β_e	0.003	0.15	
M_A	1.2	2.4	



Example Experiment 2: Quasi-parallel shock attempts at LAPD

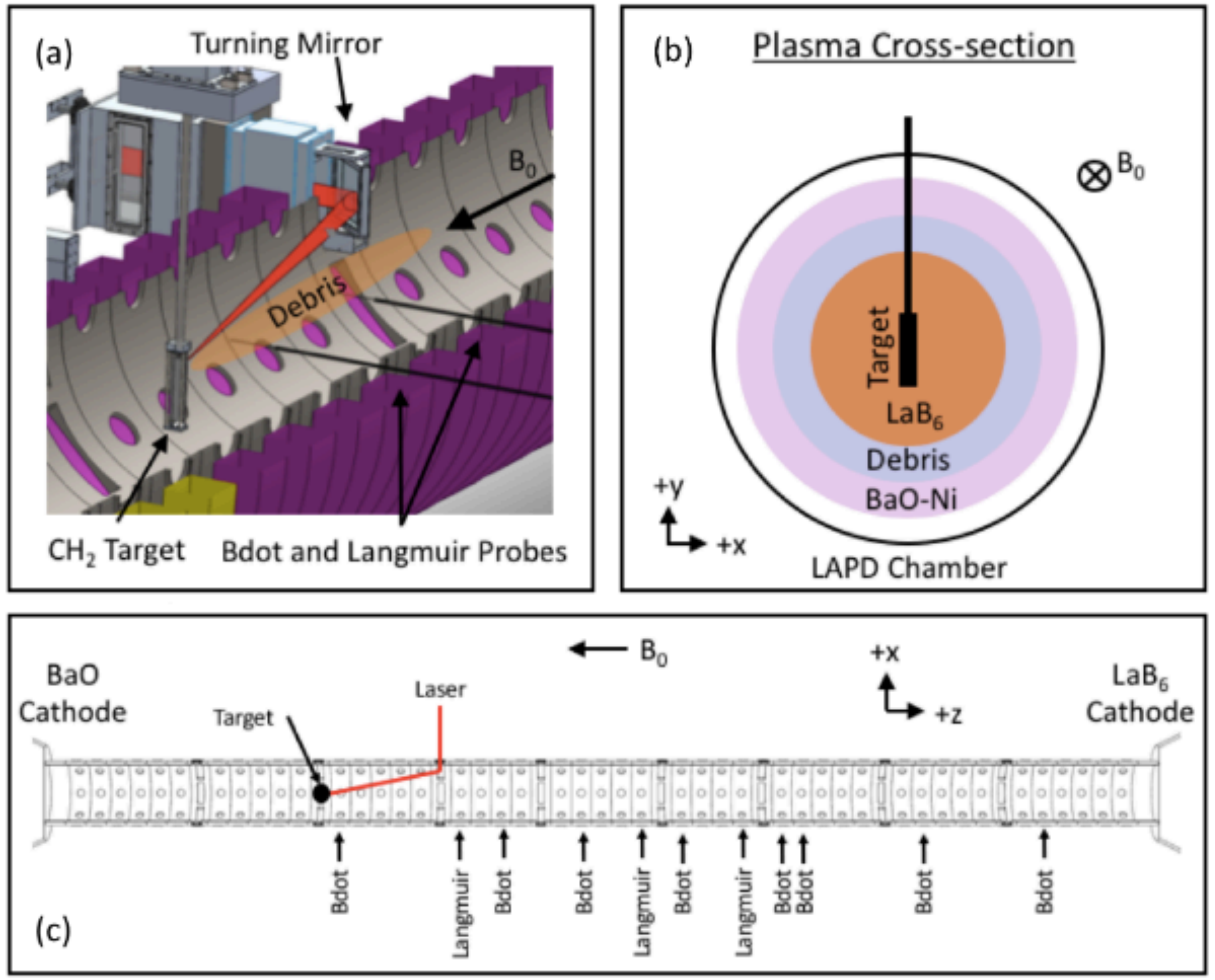


Figure 1: *a*) Schematic of turning mirror reflecting the laser beam on the polyethylene (CH_2) target inside LAPD. *b*) Cross section of LAPD with relative sizes of target, high-density helium plasma created by the LaB_6 cathode, debris/blow-off ion cloud, and lower-density helium plasma created by a BaO cathode. *c*) Cut along LAPD with positions of target, cathodes, and sample configuration of Bdot and Langmuir probes

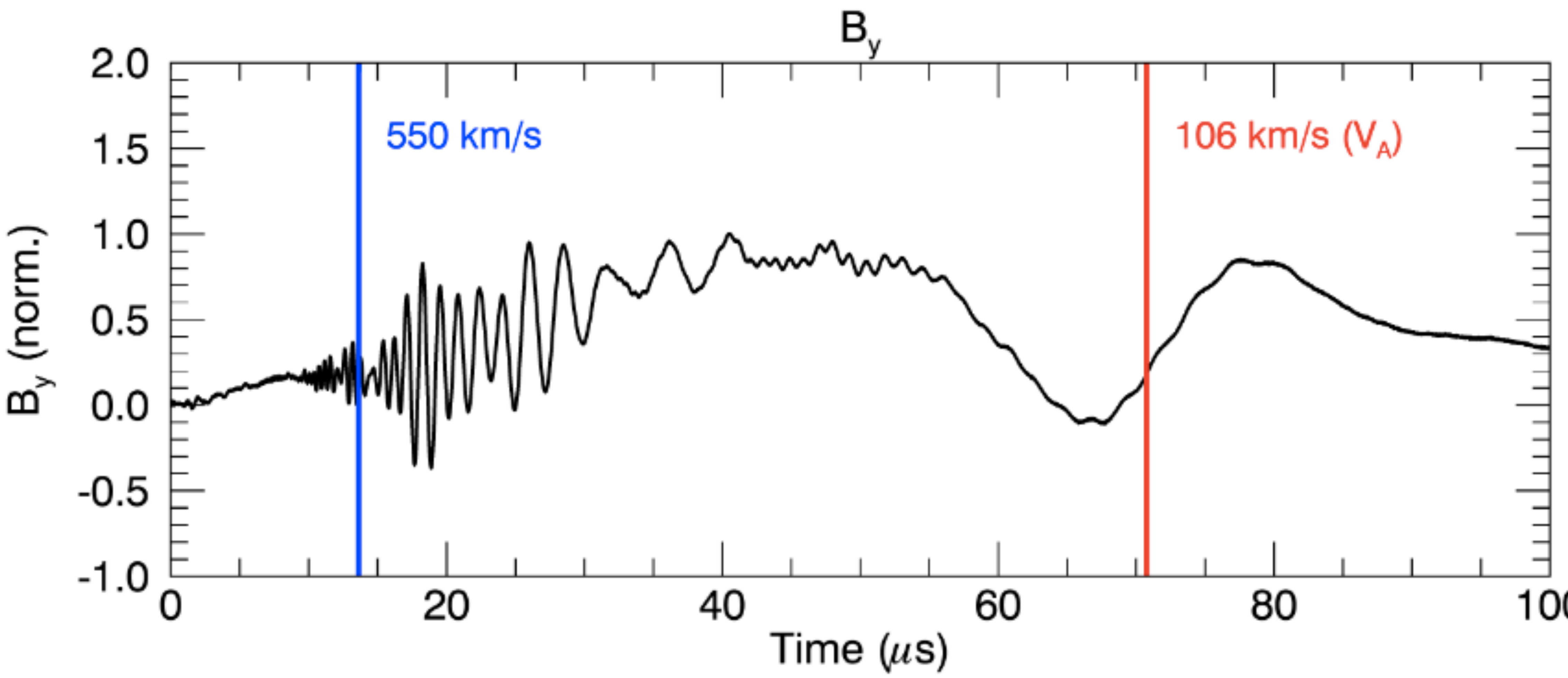


Figure 2: Sample time trace of the radial magnetic-field component measured 7.5 metres from the target on the central axis of the plasma column

Right-hand Resonant Instability with fast C++ ions, but no obvious shock formed.

M S Weidl et al, Towards A Parallel Collisionless Shock On LAPD, 2017 J. Phys.: Conf. Ser. 900 012020

Example Experiment 3: Weibel shock from counterstreaming laser plasmas

Fiuza et al., Electron acceleration in laboratory produced turbulent collisionless shocks, Nature Physics, 2020, Vol 16, 916-920

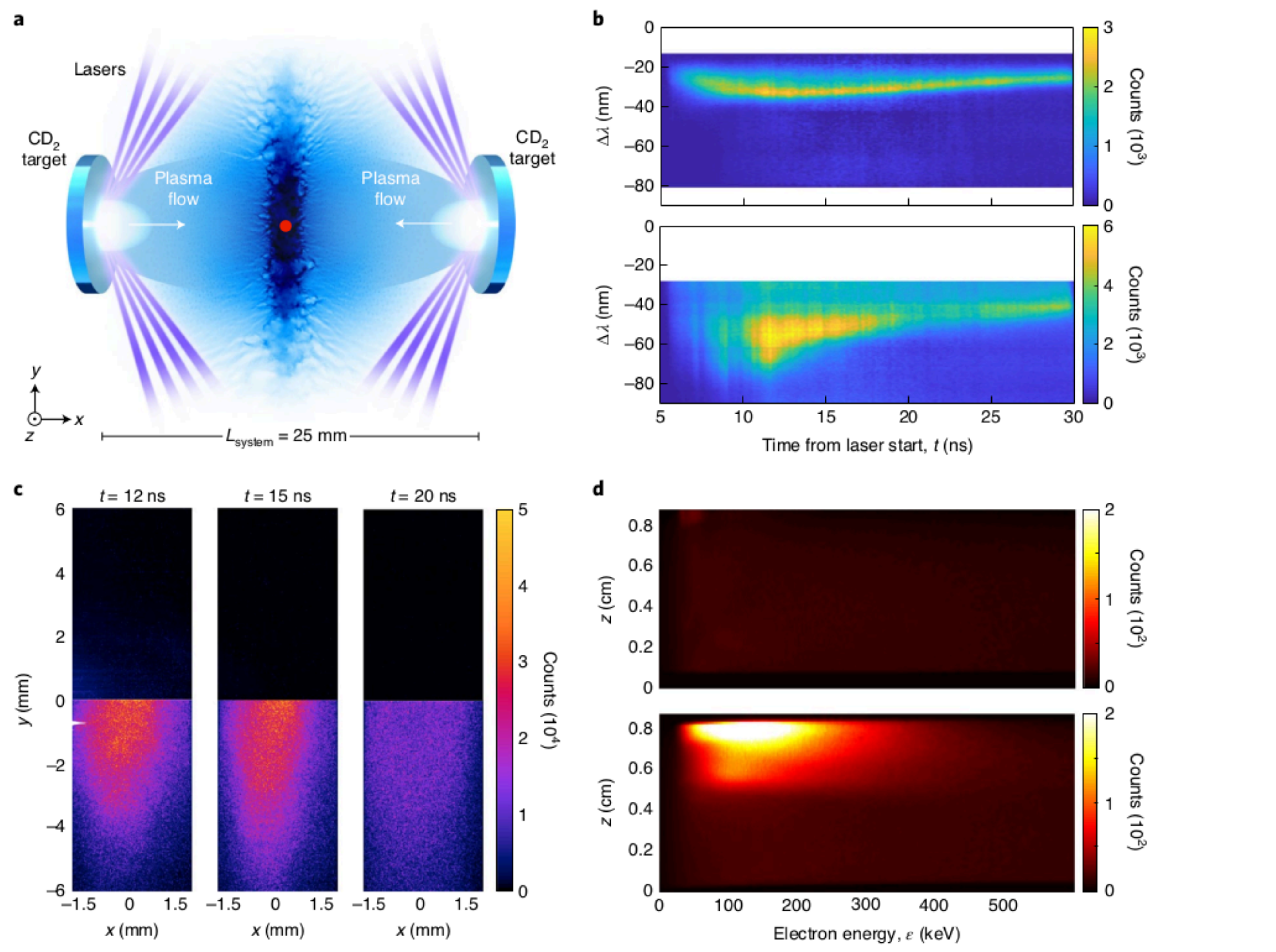


Fig. 1 | Laser-driven collisionless shock experiments. **a**, Sketch of the experimental setup with shock density structure (in blue) obtained from numerical simulation. **b**, Thomson scattering data provide measurement of the electron density and temperature at the central region (marked by red dot in **a**) for a single flow (top) and two colliding flows (bottom). **c**, Comparison of the X-ray self-emission from the plasma between a single flow (top) and colliding flows (bottom) indicates strong compression and heating of the shocked plasma. **d**, Spectrometer measurements of fast electrons (>30 keV) produced in a single flow (top) and two colliding flows (bottom) demonstrate acceleration of electrons to relativistic energies.

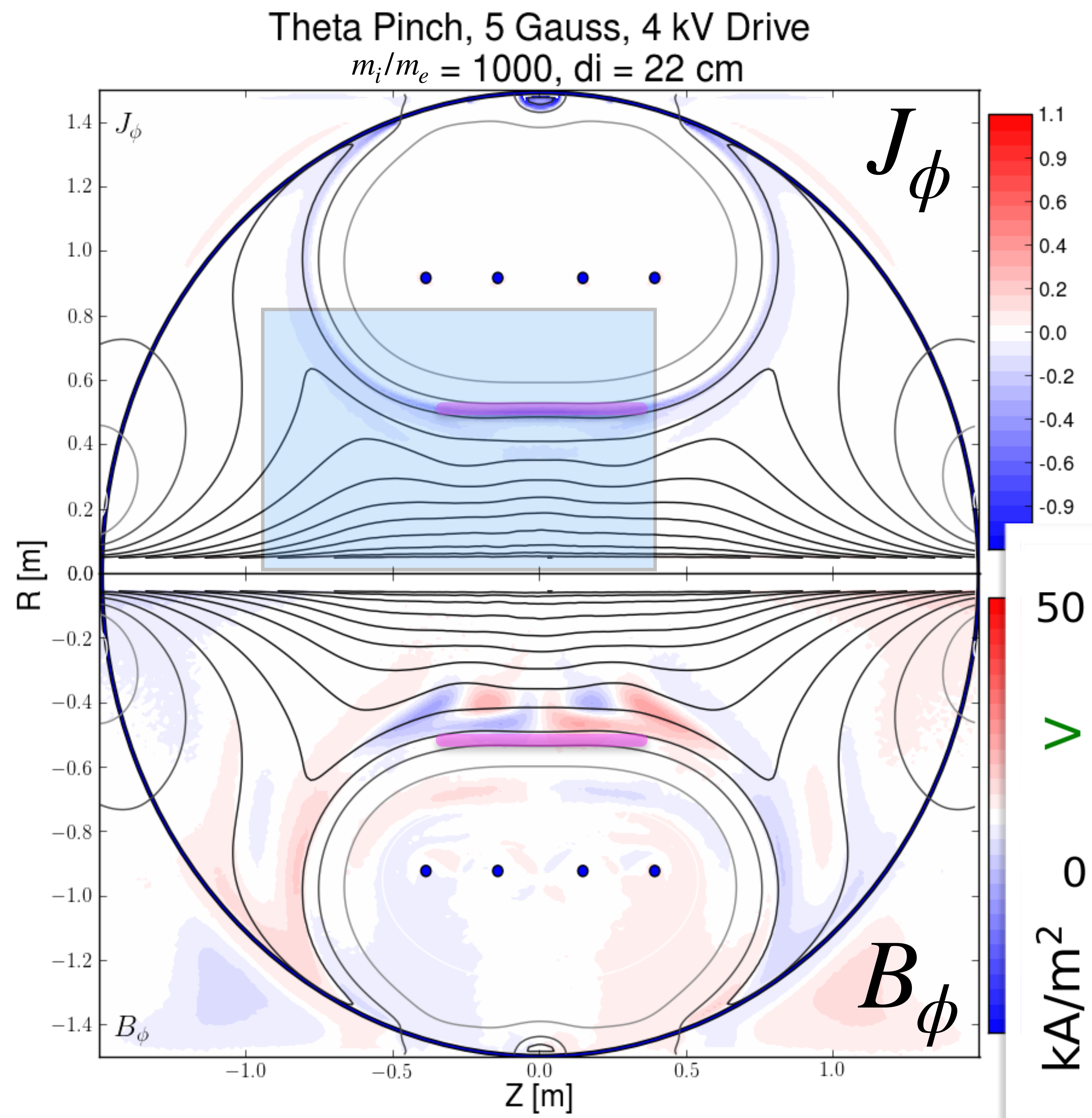
Table 1 | Comparison between plasma parameters in NIF experiments and young SNR shocks

Parameter	**NIF experiments**	**Typical young SNR (for example, SN 1006)**
Shock velocity ($\mathrm{km\,s^{-1}}$)	1,000–2,000	3,000–5,000
Ambient magnetic field (G)	2×10^{4}	3×10^{-6}
Ambient plasma density ($\mathrm{cm^{-3}}$)	5×10^{19}	0.2
Ambient plasma temperature (eV)	500	1
System size (cm)	2.5	3×10^{19}
Collisionality ($L_{system}/L_{m.f.p.}$)	0.03	0.01
Sonic Mach number (v_{sh}/c_S)	12	400
Alfvén Mach number (v_{sh}/v_A)	400	400

$$\tau_{\rm exp} \sim 10\ \mathrm{ns} \gg \nu_e^{-1} \sim 40\ \mathrm{ps}$$

Observed Weibel filaments, R-H compression, e-energization

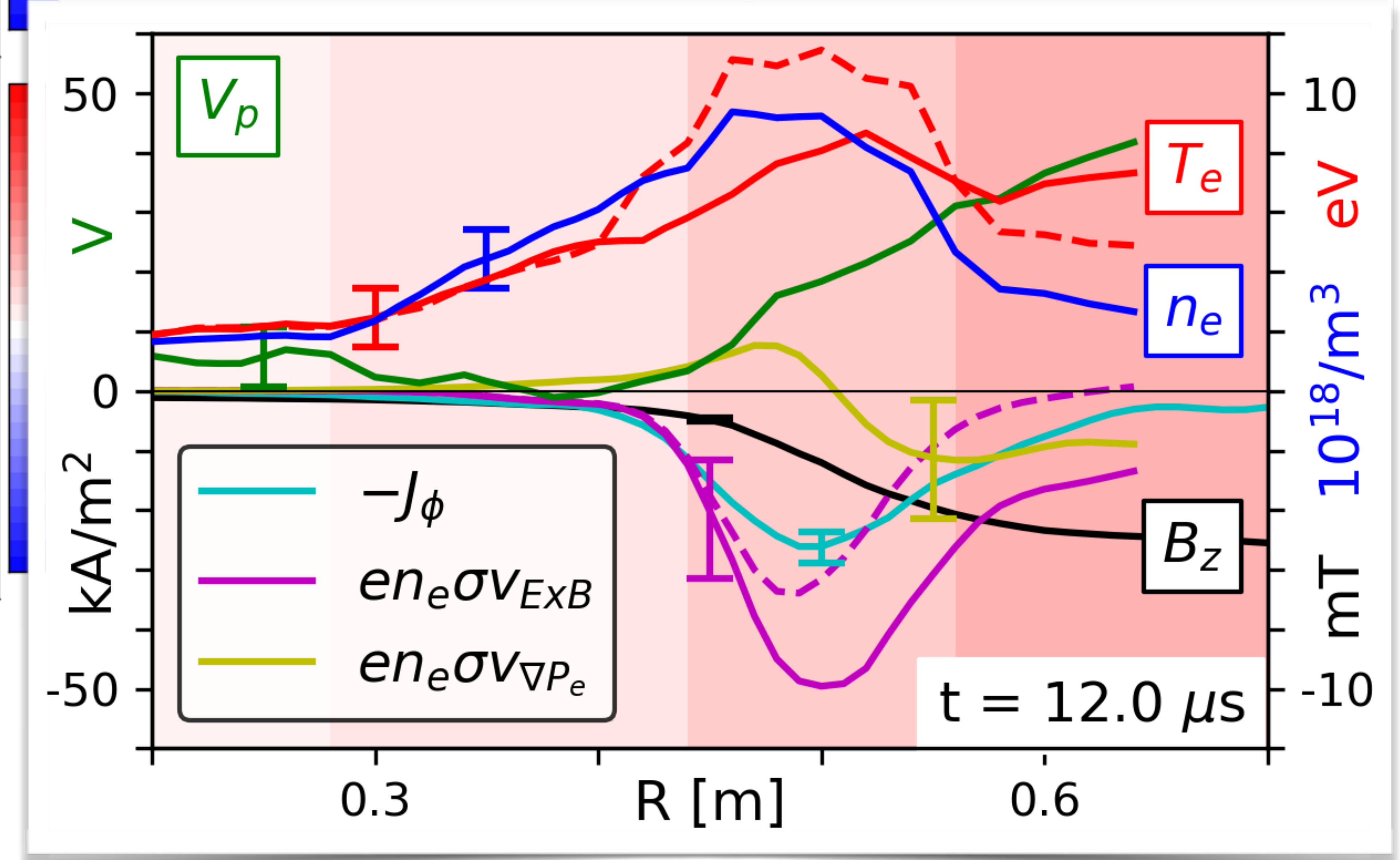
Example Experiment 4: BRB Theta Pinch: Hall physics is critical

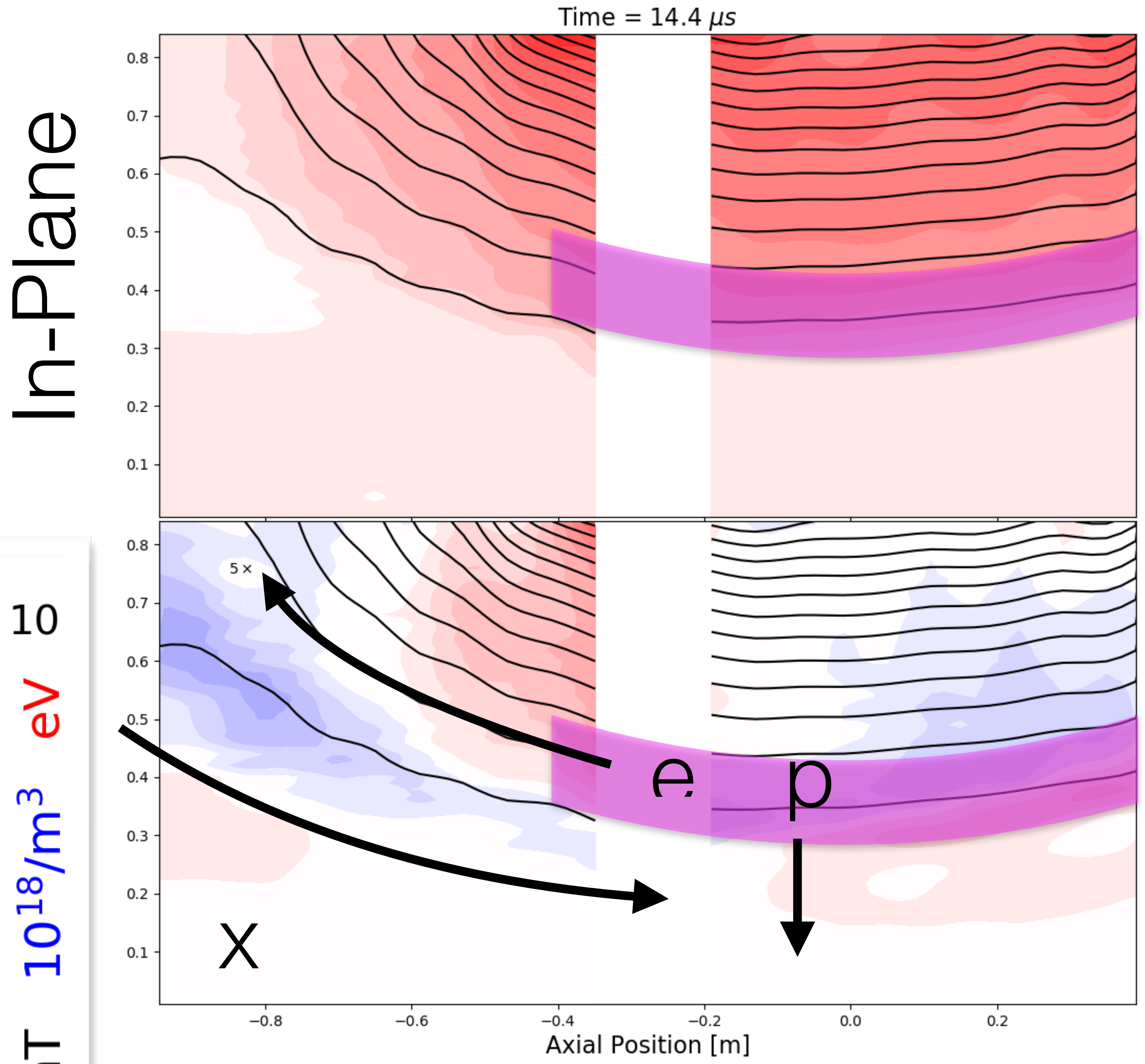


Perpendicular Shock Case

Used a magnetic piston

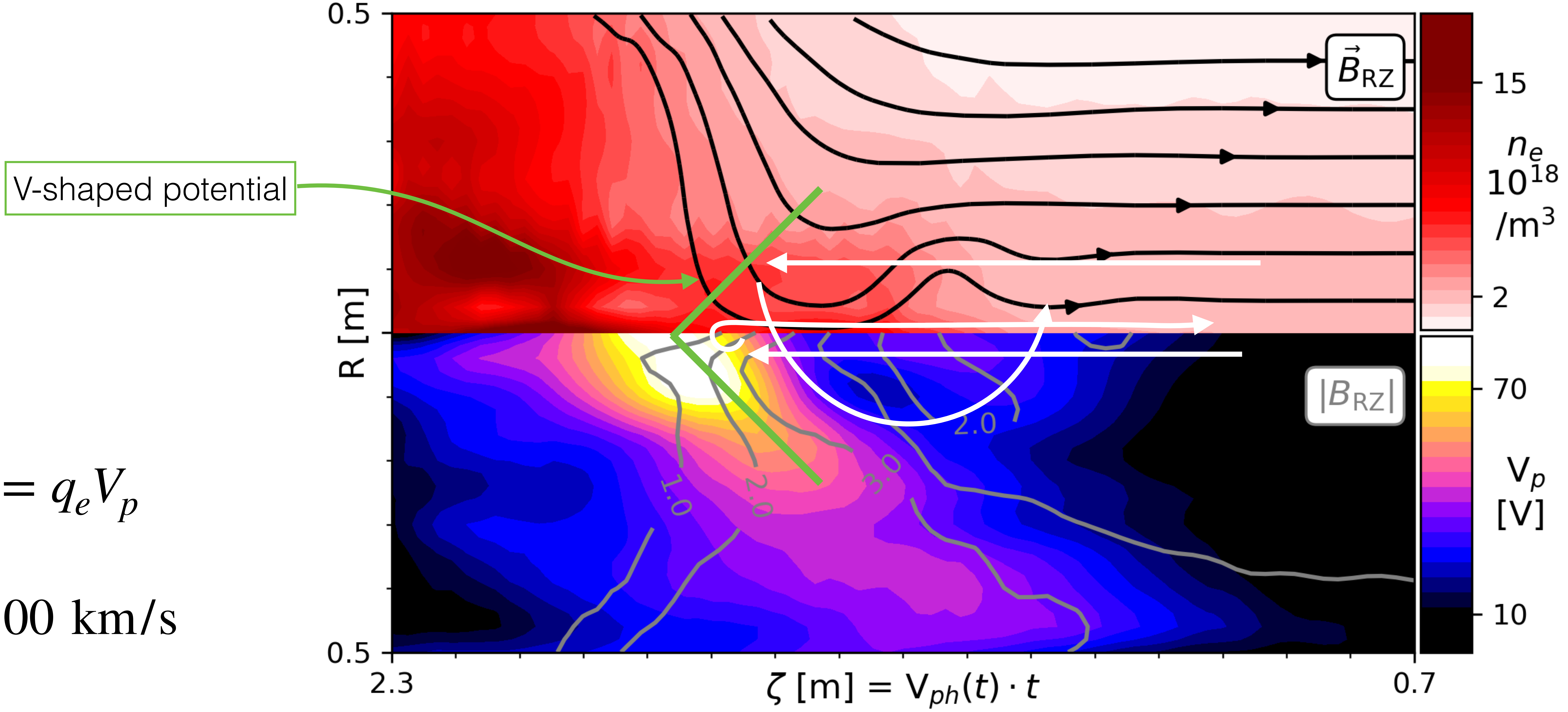
Observed Hall physics dynamics, reflected ions from ambipolar E, adiabatic electron heating.





Accepted: Endrizzi, D. et al., (2021), Laboratory Resolved Structure of Supercritical Perpendicular Shocks, PRL

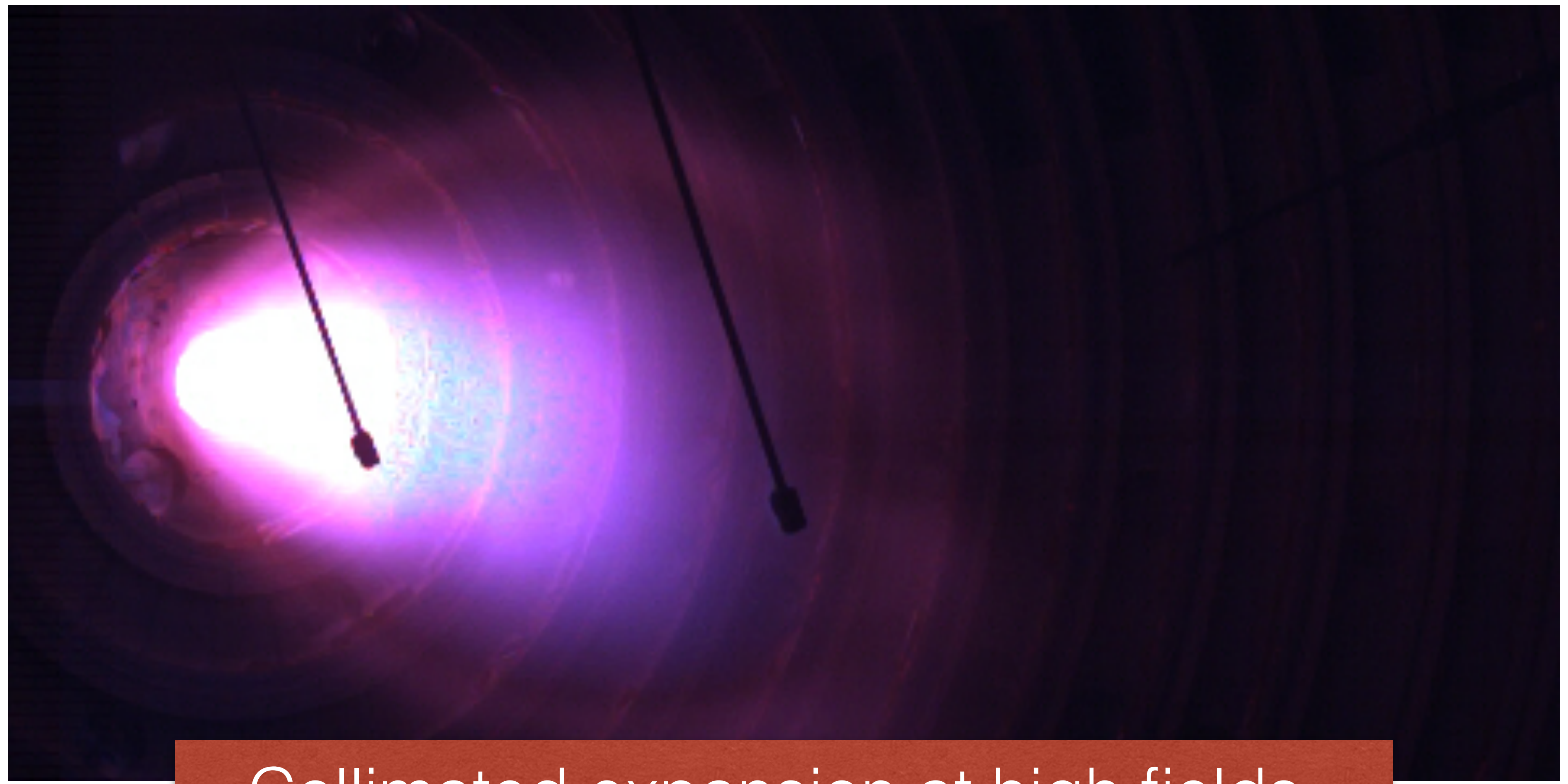
Large cone shaped potential should reflect ions



$$\frac{m_i v^2}{2} = q_e V_p$$

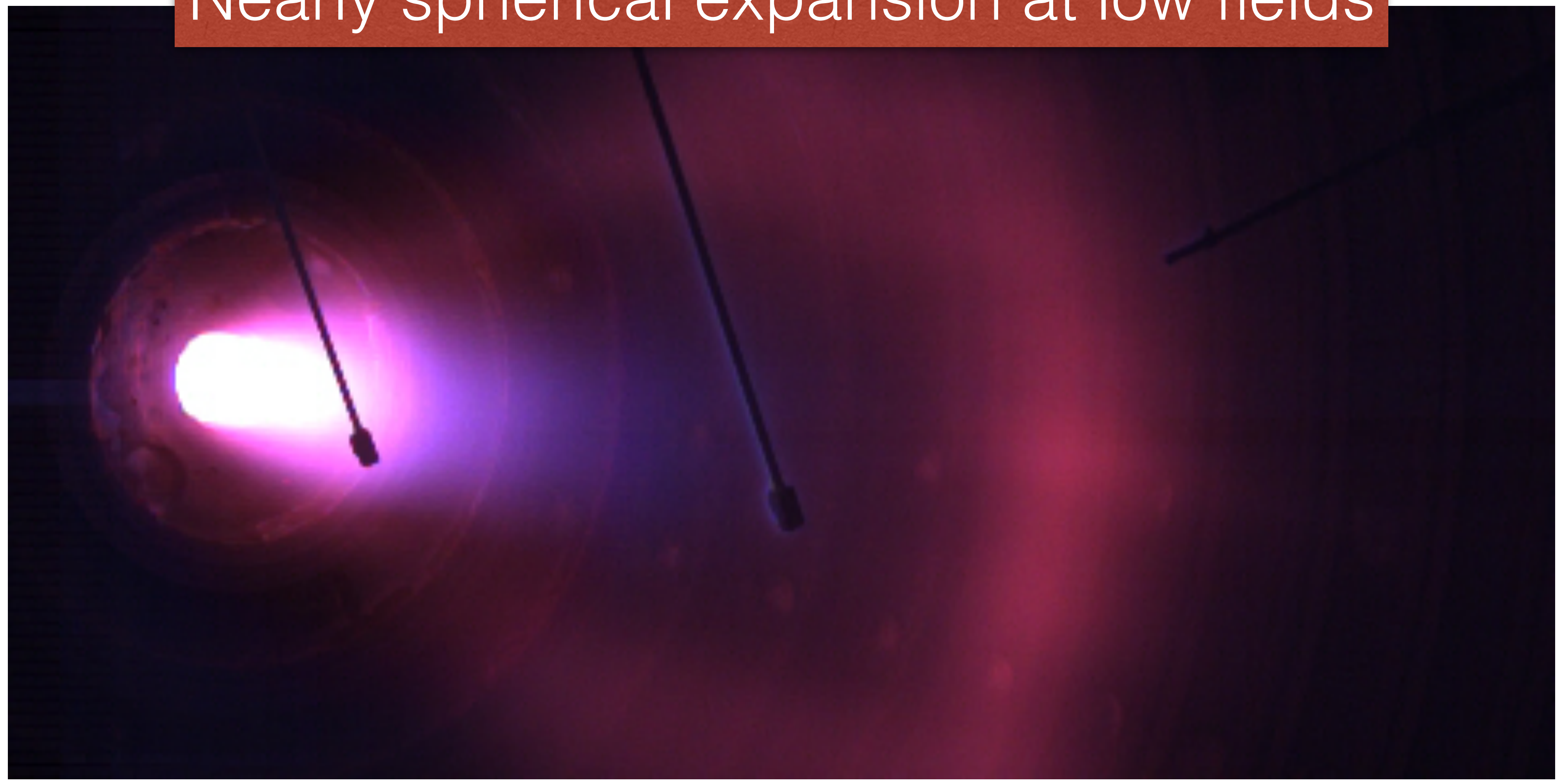
52 eV @ 100 km/s

Prior collision experiments showed our CTs have weak internal fields and could be good pistons



Shot 48289
90 G Field
Vacuum,
Bias -3.0 A

Collimated expansion at high fields.
Nearly spherical expansion at low fields



Shot 48259
70 G Field
Vacuum
Bias -3.0 A

2016 CT Into Plasma Was Tantalizingly Shock-like, but a Poor Experimental Subject

Many Agreements with Shock Theory:

- Shock travels faster than vacuum piston
- Shock strength did not exceed fluid Ranking Hugoniot limits

Problems:

- Poor repeatability -> selection bias
- Strong plasma potential fluctuations
- No Electric/Magnetic field meas.
- No T_e / T_i measurements
- Complicated CT Magnetic field